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DISCHARGE MITIGATION
STRATEGIES
FOR GE11 DETECTORS
IN THE CMS EXPERIMENT

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*“Utopia lies at the horizon.
When I draw nearer by two steps,
it retreats two steps.
If I proceed ten steps forward, it
swiftly slips ten steps ahead.
No matter how far I go, I can never reach it.
What, then, is the purpose of utopia?
It is to cause us to advance.”*

— E. Galeano

Abstract

The CMS experiment at the Large Hardon Collider (LHC) has taken successfully data for almost ten years, resulting in the discovery of the Higgs boson in 2012. The LHC will undergo a major upgrade to deliver ten times more pp-collisions in the next two decades, which has been named High Luminosity LHC (HL-LHC). To cope with the increased instantaneous luminosity and increased background levels, the CMS experiment will undergo several upgrades in the next decade. One of these upgrades is installation of Triple-GEM detectors in the forward muon system that will allow better triggering on muons, will increase the muon reconstruction, extend the coverage and increase the number of single measurements. The triple-GEM technology will be installed in three main vacant stations of the muon system: first GE1/1 during the Long Shutdown 2 (LS2) and then, during subsequent shutdowns, GE2/1 and ME0. This technology has been proven to sustain a high-rate environment with performance that fulfill CMS requirements. The Gas Electron Multiplier (GEM) is a new technology for CMS, therefore a test installation of few GE1/1 chambers was performed in 2016 as a proof of concept, commonly referred as the *Slice Test*. The aim of this thesis arises from the necessity to address a problem emerged during the slice test. During the two years of operation, an increasing read-out channel loss has been observed. This can potentially compromise the muon detection efficiency during HL-LHC and will worsen the overall muon system trigger capabilities.

In this thesis I report on the study of the origin of the channel loss and the following R&D program on the possible mitigation strategies. As a result of the study, we proposed and tested a minimal change implementation on the GE1/1 detectors design, that ensures a much stronger endurance of the read-out electronics to discharges, without compromising the schedule for the GE1/1 installation. We also proposed a new design for the GEM foil as a definitive mitigation strategy for the upcoming detectors of GE2/1 and ME0. Finally, the observations on discharges we made throughout the research program, contribute to shed new light on the still not well understood process of discharge propagation in GEM detectors.

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CHAPTER 1

Physics at LHC and the CMS experiment

The LHC at the European Organization for Nuclear Research (CERN), is a circular proton-proton collider. It was designed to operate at highest luminosity and energy accessible to accelerators, in order to study the sub-nuclear structure of the matter which is, at the moment, described well by the Standard Model (SM) theory.

1.1 The Standard Model and Electroweak Symmetry Breaking

The SM is a theory that describes all the known elementary particles and the fundamental interactions that exist between them, with the exception of gravity. The SM brought order into the description of the forces between particles: an essential discovery was that the strong, electromagnetic and weak forces can be derived from the postulate of gauge symmetries [1].

Elementary Particles

In the SM matter consists of fermions, that come in two groups: leptons and quarks, which are both half-integer spin particles. Both groups are further subdivided in three families (or generations) with two particles each, based on shared intrinsic properties. Each lepton family is composed by a negatively charged particle (e^- , μ^- , τ^-) and its associated neutral particle (ν_e , ν_μ , ν_τ). Instead, each quark family consists of two opposite charged particles, $+1/3$ and $-2/3$, with the positively charged one always displayed as first in the doublet: (u, d), (c, s), (t, b) [2]. For each of the described particle, the SM foresees (confirmed by the experimental results) an associated *anti-particle* with opposite charge. Quarks and leptons are distinct by the fact that the latter, in contrast to the former, are *not* sensible to the strong interactions [3]. Fig. 1.1 shows the fundamental particle included in the SM, with specifying some of their physical properties.

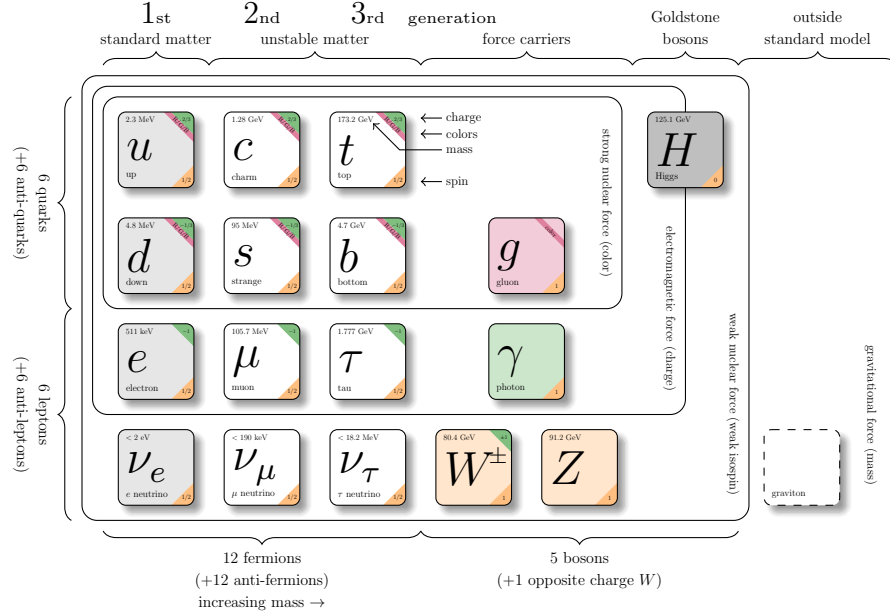


Figure 1.1: The fundamental particles of the SM together with the carriers of the fundamental forces and the Higgs boson. The rounded box delimits the SM; outside it we find the *graviton*, the hypothetical particle that mediates the gravitational force, which is not included in the SM.

Fundamental Forces

The study of the elementary particles is tied to the study of the fundamental forces. In the SM, the weak, the strong and the electromagnetic interactions are described by quantum theories based on a symmetry postulate: the principle of *local gauge invariance*. In simple terms it says that these theories are invariant under a particular class of transformations called *gauge transformations*, which allows their description within the same mathematical formalism. In such gauge theories the interactions are induced by an exchange of energy quanta, called gauge bosons, which are 1-spin particles [3]. The SM describes these interactions with two gauge theories: the ElectroWeak (EW) theory that unifies the *electromagnetic* and the *weak* force, and Quantum Chromodynamics (QCD) which describes the strong interactions. The EW theory includes the γ , the W^+ and W^- and the Z^0 as gauge bosons while the carriers of the strong force are the gluons, which are accommodated in the QCD. Finally to have a complete theory of particles and fields, able to consistently attribute mass to the particles, one has to introduce another class of spin-0 particles called the *Higgs bosons* [3], which will be further detailed in the next section.

1.1.1 The Electroweak Symmetry Breaking

The electromagnetic and the weak force were unified using $SU(2) \times U(1)$ as a gauge group. This achievement was firstly reached by Glashow in 1961 [4]. However the theory did consider the elementary particles and the weak force gauge bosons ($W^\pm$, Z^0), as massless particles. The theory was indeed not realistic: the mass of a gauge boson is inversely proportional to the associated force range, therefore the weak force was modeled as an infinite range force. This is in contrast with the fact that the weak interactions, at low energy, are described with point-like Fermi theory [5]. Explicitly adding the masses terms, breaks the gauge invariance and leads to a not normalizable theory.

A possible mechanism to generate masses for the weak force gauge bosons was proposed by Englert, Brout and Higgs [7, 6] and independently by Guralnik, Hagen and Kibble [8], and was then incorporated in the SM by Weinberg and Salam [9]. It introduces a doublet of complex scalar fields invariant under $SU(2) \times U(1)$, then constructs the Lagrangian density for such a field invariant under $SU(2) \times U(1)$. However the ground state, which is connected to the non-zero vacuum expectation value of the field, breaks the $SU(2)$ invariance, causing the so called spontaneous ElectroWeak Symmetry Breaking (EWSB). When this complex scalar field is coupled with the gauge bosons and the fermions, the mass terms for $W^\pm$ and Z^0 arises as well as the mass term for the charged leptons, while the neutral leptons and the γ remain massless. Finally a massive neutral 0-spin particle emerges, which is the Higgs particle. One of the most important prediction of the SM about the Higgs boson, is the fact that its coupling constants with the fermions scale with the mass of the particle, while for the gauge bosons, the coupling constants scale with the mass squared. Additionally the EWSB allows the self-coupling of Higgs bosons in the SM.

1.1.2 Discovery of the Higgs Boson

The gauge bosons $W^\pm$ and Z^0 were discovered at CERN in 1983. While on 4th July 2012, both A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS) experiment, announced the discovery of a new neutral particle with invariant mass peak close to 125 GeV [11, 10]. The spin-parity $J^P = 0^+$ [12], the coupling factors [13] and the decay rates [14] measured for the new observed boson were compatible with the SM Higgs boson. The measurement of the Higgs potential and of the Higgs self-couplings, will certify that it is the SM predicted one. Due to the incredibly low cross section of such events, we will have to wait for the HL-LHC upgrade, to shed light on these questions.

1.2 Motivations for Physics Beyond the Standard Model

The SM still has open questions that are inspiring new models and theories. The Higgs mass found at $\simeq 125 \text{ GeV}$, for example, opens a new unsolved puzzle in the SM, known as the *hierarchy* or *naturalness* problem. In fact a large fine tuning between the bare Higgs mass and its radiative corrections, is required in order to leave the measured Higgs mass in the 100 GeV range. New theories, beyond the SM, are addressing this issue and some of them predict new physics in the TeV energy scale. Hence we need to push the collisions energy and look for evidence of deviations from the SM in order to ultimately assess the nature of the observed Higgs boson.

Among other topics that still lack explanation, there is the *high* number of free parameters of the theory (i.e. 25), the number of quark and lepton generations, the quantization of the electric charge, the missing terms in the QCD Lagrangian that would lead to the Charge-Parity (CP) violation in the strong interactions and Dark Matter (DM).

The Strong CP problem is another fine tuning problem. The QCD Lagrangian accomodates one factor that would allow the CP violation modulated by a factor θ . However the current limits on the neutron electric dipole moment say that $|\theta| \leq 10^{-10}$ [15]. A possible solution for the problem was proposed by Peccei and Quinn in 1977 with a spontaneous breaking of a global $U(1)_{PQ}$ and the consequent arise of a new particle, the *axion*, as a Goldstone boson. The axions are candidates for the DM, with their mass that is expected to lie in the $2\text{-}200 \text{ } \mu\text{eV}$, hence at least 7 order of magnitude smaller than the electron mass. The existence of DM instead, had its earliest evidence in the early 1900, with the observation of the deviation of trajectory of luminous objects from the trajectory they would have had if their only gravitational attraction was due to visible objects. Candidates for non-baryonic DM include primordial black holes, axions, sterile neutrinos and Weakly Interactive Massive Particle (WIMP)s [2]. In the foreseeable future we need to challenge the SM by searching evidence of theories beyond it at the highest available energy, in order to overcome the limitations formerly described. The effort for a deeper validation of the SM is also shared by the CMS experiment at CERN, which is briefly described in the next section.

1.3 The Compact Muon Solenoid (CMS)

CMS [16] is one of the four main experiments installed at the LHC. It is a general purpose experiment apparatus that tries to tackle the fundamental puzzles of modern physics, such as the DM origin, the existence of physics beyond the SM

in the TeV energy scale and the origin of the mass of the particles.

The overall detector dimensions are 21.6 m of length and 14.6 m of diameter for a total weight of 12500 t . Fig. 1.2 shows an overview of the whole detector with its subsystems. The central feature of the experiment is a large superconducting solenoid, providing a 4 T magnetic field that allows to bend the muon trajectories before they reach the muon system. The magnet return yoke, which confines the magnetic field, is interleaved with four layers of muon detectors while, in the solenoid cavity, are the inner tracker, the electromagnetic and hadronic calorimeters. The general structure of these subdetectors will be discussed in the next paragraphs, with a focus over the muon system and its upcoming upgrade.

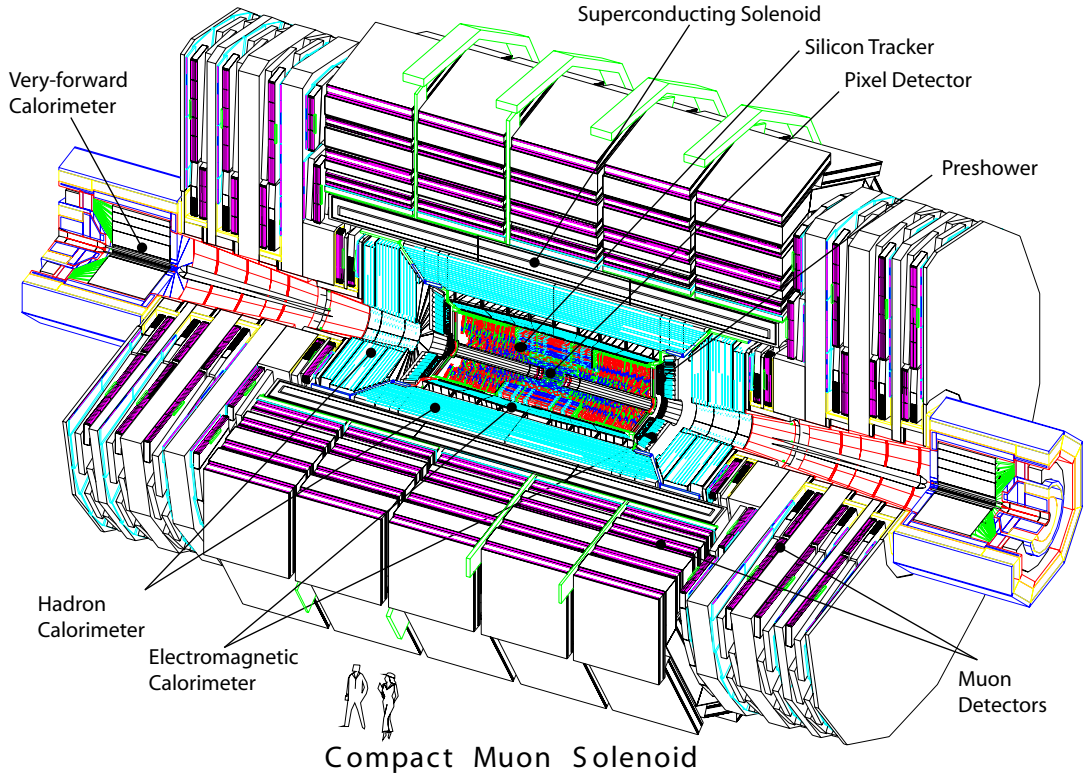


Figure 1.2: A perspective view of the CMS detector [16].

1.3.1 The CMS subsystems

Fig. 1.3 shows a transversal view of a quadrant of the CMS experiment, highlighting the detector technologies detailed in the following paragraphs.

The **inner tracking system** surrounds the Interaction Point (IP) and it is designed to provide a precise measurement of the trajectory of the particles produced in the collisions. It is entirely based on silicon detectors in order to cope with the necessity of a fast response, the high granularity, and the harsh radiation environment. Thus three layers of pixel detectors and ten layers of silicon strips are installed in the

barrel, completed with additional disks in the endcaps for a total of 200 m^2 of active silicon area. This gives an overall acceptance of the tracker up to $|\eta| \leq 2.5$.

The **electromagnetic calorimeter** (ECAL) is a hermetic calorimeter made of 61200 $PbWO_4$ crystals in the barrel and more than 7000 in each of the two endcaps, covering the pseudorapidity range $|\eta| \leq 3.0$ [16]. As the electrons and photons cross the detectors, they begin an Electromagnetic (EM) shower, in which their energy is converted in photons. Thus the measurements of the particle energy is possible by photon detection, carried out with photodiodes and phototriodes that match the photons wavelength. The design of ECAL was also driven by the capability to measure the decay of the Higgs boson (only *predicted* at the time) into two photons, with a sub-percent mass resolution.

The **hadron calorimeter** (HCAL) is based on interleaved brass absorber layers and scintillator layers in order to measure the hadron jets energy. It takes part in the detection of the missing energy, that might point to the failure of detection of one of the final state particles, such as neutrinos but also as non-interacting new particles. The light emitted by the scintillators is then read out by photodiodes, for the energy evaluation. The HCAL barrel and endcap regions, cover up to $|\eta| \leq 3$. Additionally, a Cherenkov-based calorimeter, is located outside the solenoid in order to increase the total hadronic absorber material and enlarge the pseudorapidity coverage up to $|\eta| \leq 5.2$

Muon System

The muon system has the crucial duties of muon identification, muon momentum measurement and, together with the calorimeters, the overall triggering. Since many interesting physics decays lead to muon final states, the muon system has been entrusted with a central role in CMS and has been designed with the wide angular coverage $|\eta| \leq 2.4$.

The intense magnetic field causes the bending of the muon trajectory allowing a good momentum resolution. However the return-field yoke, although keeps CMS compact by keeping the flux lines close to the solenoid, complicates the detection and reconstruction of high energy muons due to the increased shower probability. The muon system is installed on two main regions: the *barrel* and the *endcap* (see Fig. 1.3), and makes use of different gaseous detector technologies. The *wheels* that surround the barrel are instrumented with the Drift Tube (DT) technology for precise measurement and triggering and Resistive Plate Chamber (RPC) technology for coarse measurement and triggering.

The CMS DT chambers have as a fundamental cell the rectangular wire chambers. When a muon crosses the DT cell, it produces electron-ions pairs in the gas. The position of the muon with respect to the wire is evaluated by the drift time of the produced charges. Thanks to the design of the CMS DT chambers, the uniformity of

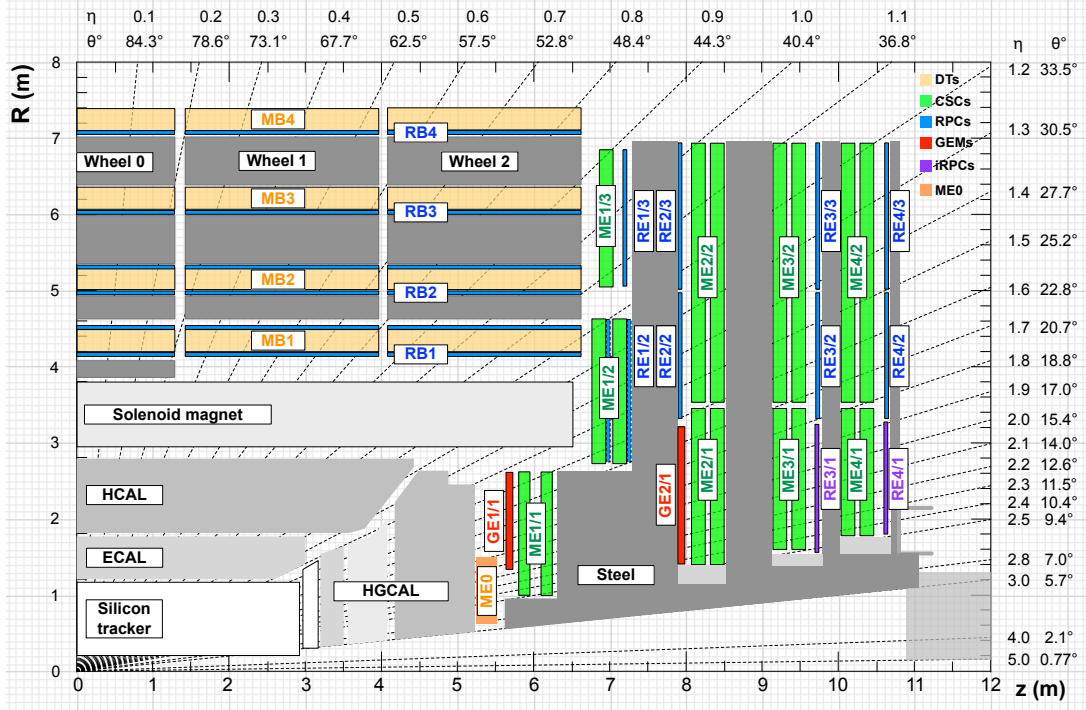


Figure 1.3: A quadrant of the CMS muon system including the Phase-2 upgrades (RE3/1, RE4/1, GE1/1, GE2/1, ME0). The magnet yoke is represented by the dark gray [17].

the electric field is granted, which allows a space resolution of $250 \mu\text{m}$ for the single cell, while it reaches $100 \mu\text{m}$ for a whole chamber made by 8-12 cells depending on the geometrical constraints [16].

The ions drift time limits the rate capability of the DTs and the presence of an intense magnetic field (which in the wheels is shielded by the yoke) affects the drifting trajectories of the charges. Thus the RPC and the Cathode Strip Chamber (CSC) technology has been installed in the endcaps.

The CSC provide the functions of precision muon measurement and muon trigger and can operate at high rates and in large and non-uniform magnetic fields. The CMS CSC are Multi-Wire Proportional Chambers designed with Cathode Strips readout. Each of the 6 gaps that form a CSC chamber, is made with one wire anode plane sandwiched between two cathode planes, one of which is segmented in strips. The CSCs are capable of spatial resolution up to $75 \mu\text{m}$ and can stand particle rates up to few tens of kHz/cm^2 .

The RPC consists of a gaseous parallel-plate detector with a time resolution of the order of few nanoseconds. Therefore they provide a fast and independent trigger in the range $|\eta| \leq 1.6$ of the muon system. 1056 RPC detectors are used in the muon system, resulting in a total active area of 3500 m^2 is used in the CMS Muon Spectrometer. The CMS RPC consists of a 2 gaps chamber operated in avalanche

mode with one shared pick-up read out in between, thus the total induced signal is the sum of the 2 single gap signals. Therefore the single gaps can operate at lower gas gain granting a detector efficiency higher with respect to the single-gap.

1.3.2 The Trigger System

The LHC delivers proton-proton collisions at a rate of 40 MHz. The CMS experiment collect about 1 MB for each proton-proton collision, that would lead to an overall amount of 40×10^6 MB recorded each second, technically impossible to stream to disk. Furthermore, not all the events give a significant scientific contribution, since most of them contain low-energy collisions rather than inelastic hard scattering processes. The reduction of the stored event rate is carried out by the trigger system [18].

The trigger system aims to select the potentially interesting events and to reduce the stream of stored data to a manageable few hundreds of MB/s. The CMS trigger system consists of two levels, called the Level 1 (L1) and the High Level Trigger (HLT). The L1 uses the preliminary and coarse reconstruction information from the muon system and the calorimeters, while the tracker is not involved since its multitude of channels would slow down the process. The best reconstructed candidates are then rejected or accepted, depending on their transverse energy and transverse momentum. The L1 trigger system takes a decision in less than $3.2 \mu\text{s}$ and carries a reduction of the event rate from 40 MHz to less than 100 kHz. The events selected by the L1 trigger are then sent to the HLT, which is a complex software algorithm executed by a computer farm. By including all the CMS subsystems, the algorithm is capable of select the best candidates depending on the physics of interest. The selection process is completed in few milliseconds and the resulted event rate is of few hundreds of Hz, which are finally stored on the disk.

The L1 trigger, as discussed above, is the one that cuts the most of the events. The goodness of the selection is directly affected by the muon system performance, both in terms of speed and quality of the reconstruction.

1.4 Upgrade of the forward muon station

The LHC luminosity will be stepwise augmented in order to tackle the open questions presented in the Sec. 1.2. The LS2 has just started this year (2019), and will last until the end of 2020. In 2021 the LHC Run 3 will start, with luminosities up to $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Finally, at the end of the Long Shutdown 3 (LS3) (middle 2026), will begin the next phase of LHC operations, called HL-LHC [19], that foresees values up to $5 - 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ for the instantaneous luminosity and is expected to last till 2038 (see Fig. 1.4). In order to maintain the excellent performance of the CMS muon detection in the high luminosity regime, an upgrade

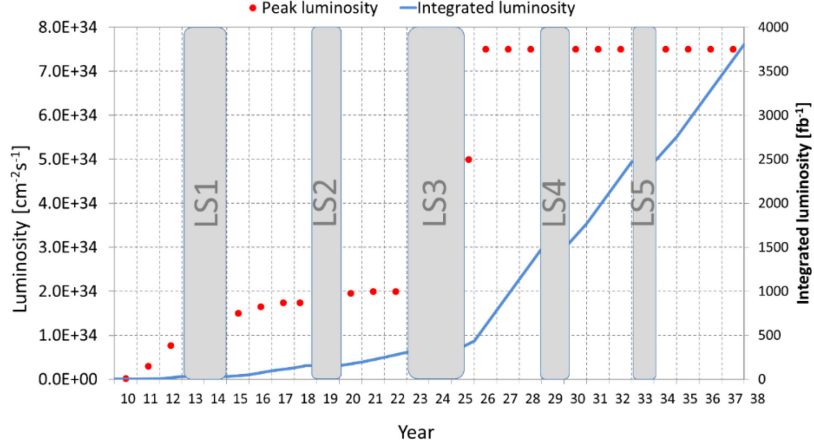


Figure 1.4: Expected luminosities for LHC across the years [19].

of the muon system is required. The existing DT, CSC, and RPC detectors are essential to fulfill the CMS physics program, therefore, in order to grant that their performance will be maintained at high luminosity, several upgrades of their electronics will be carried out [17].

During the HL-LHC, with the goal of providing a reliable triggering on muons in the very forward regions, the number of hits measured per track will be increased. The muon detector upgrade will recover an effective muon system in the forward region with new muon detectors in the station GE1/1, GE2/1, RE3/1, RE4/1 and ME0 that will extend the acceptance of the muon system up to $\eta = 2.8$ (see Fig. 1.3).

1.4.1 GEM detectors for the Muon Upgrade

Due to the large area needed to be instrumented, silicon based technologies result to be too expensive. Moreover, the high rate of the incident particles foreseen in the most forward region, approaches and in some cases exceeds the capabilities of the CMS CSC and RPC detectors [17]. Therefore the GE1/1 and GE2/1 stations will be equipped with GEM detectors, not yet mature at the time of the design of CMS, while the RE3/1 and RE4/1 stations will be instrumented with the improved RPC (iRPC).

The GE1/1 station will be instrumented during the LS2, the GE2/1 during the Year-End Technical Stop (YETS) of 2021 and 2022, while the ME0 installation is planned for the LS3. An earlier installation of GE1/1 called *Slice Test*, has been successfully operated during 2017-2018 and has provided a first functional experience of Triple-GEM detectors under the CMS conditions. I will discuss in detail the results and the lessons learnt during the slice test in Sec. 4.1, while a detailed description of the GE1/1 project is discussed in the next section (Sec. 1.5). The triple-GEM detectors for the muon system upgrade will provide a detection

efficiency of 97% with a time resolution up to 7 ns and will easily operate in the forward CMS region where a maximum rate of 150 kHz/cm^2 is expected (on ME0 at $|\eta| = 2.8$). The studies on the GEM technology that have taken place to fulfill the CMS requirements, have contributed to the boost in the development of such detectors. As a result, nowadays the GEM is a mature and robust technology, with strong tracking capabilities in high-rate applications [17].

1.4.2 GEMs impact on the trigger

The higher rate of incident particles during HL-LHC, will lead to an increased probability of low transverse momentum particles being reconstructed as high transverse momentum muons. This will mostly affect the trigger in the forward region $|\eta| > 1.6$, due to the reduced path length in the magnetic field. Furthermore, the actual trigger system is inefficient for muons tracks produced in decays of long-lived particles (impact parameter in the mm range), expected from some model beyond the SM.

Using the new GE1/1 chambers together with the existing CSC ME1/1, allows a good rejection of the mismeasured muon backgrounds, that contribute the most in the muon trigger rate. The new GE2/1 detectors, to be installed next to the existing CSC ME2/1, will provide a second muon direction measurement that will further improve the trigger efficiency, and allow for a dedicated trigger on displaced muon signatures. Fig. 1.5 shows the great reduction in the trigger rate thanks to GE1/1. Any malfunctioning in the CSC & GE1/1 hit reconstructions, would lead to a local increase in the trigger rate. However thanks to the installation of GE2/1, the good trigger performances will be granted even in this unfortunate scenario.

The most forward region will be instrumented with ME0 detectors, six layers of triple-GEM chambers that will extend the current muon coverage into the region $2.4 \leq |\eta| \leq 2.8$. Generally, there are two distinct sources of background misidentified as muons: charged particles produced in Pile Up (PU) interactions and long lived neutrons and their byproducts. At every Bunch Crossing (BX), the PU particle density approximately produces 12 real muons and 50 electrons or hadrons that make hits on the ME0 detectors. This background source can be reduced by requiring a hit in at least 4 out of 6 ME0 layers. The long lived neutrons and their byproducts would induce approximately 1000 ME0 hits at every BX and this could lead to a large background contribution due to the combinatorics. However this background contribution is reduced to a negligible level if we add the requirement of segment hits in at least four layers. Thanks to the six ME0 layers, this only cause a sub-percent loss of muon segment reconstruction.

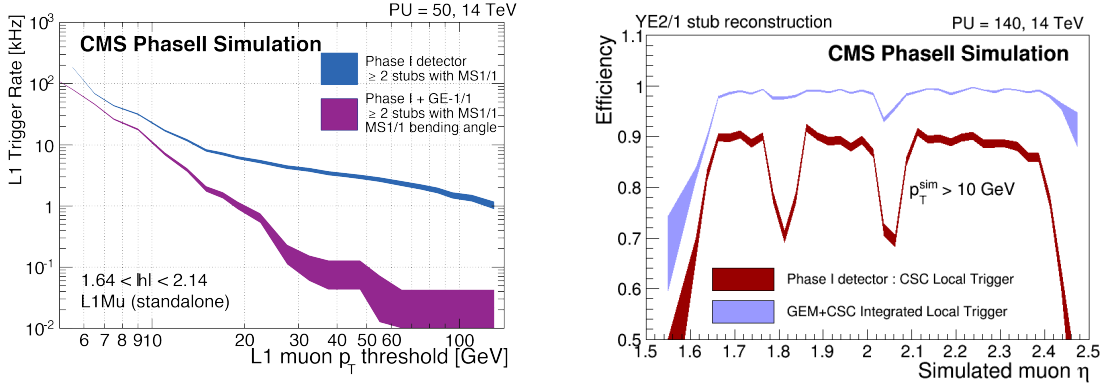


Figure 1.5: Effect of the GEM detectors on the L1 trigger rate. On the left the trigger rate reduction achieved with the muon direction measurement from GE1/1 and ME1/1 chambers. On the right the reconstruction efficiency as a function of muon η , using the CSC only or both the CSC and the GEM [17].

1.5 The GE1/1 upgrade of the muon spectrometer

The GE1/1 station, which is the first endcap muon station, will be equipped with triple-GEM detectors during the LS2. Fig. 1.6 shows the design of a single GE1/1 detector. In the GE1/1 muon station a pair of such detectors is combined in a *superchamber*. This provides two measurements planes and ensures an higher detection efficiency. Due to the mechanical constraints, the 72 superchambers installed in each endcap, are alternately long ($1.55 \leq |\eta| \leq 2.18$) or short ($1.61 \leq |\eta| \leq 2.18$), each with a 10° angular coverage. As can be seen in Fig 1.3, the GE1/1 hit rate is expected to vary along its $i\eta$ partitioning. The readout plane is segmented in 24 sectors arranged in $3i\phi \times 8i\eta$ partitions, with a total of 128 strips each. Each partitions is read by one VFAT, which will be described in much details in Sec. 4.2.1. Fig. 1.9 shows the segmentation of the readout board and the VFAT positioning.

An extensive R&D campaign has taken place between 2010-2014, with a total of 10 generation of prototypes, in order to obtain the world first 1 m-class GEM detector. One of the crucial innovations was the tensioning of such large foils with *pull-outs* [20] making this detectors the first large GEM detector without any glued components. This system provides uniform gaps spacing, that are essential in order to get uniform performance all over the detector area. The final gap configuration is 3/1/2/1 fluxed with Ar/CO₂ (70 : 30).

The GEM foil surfaces oriented towards the readout board, consist of a single

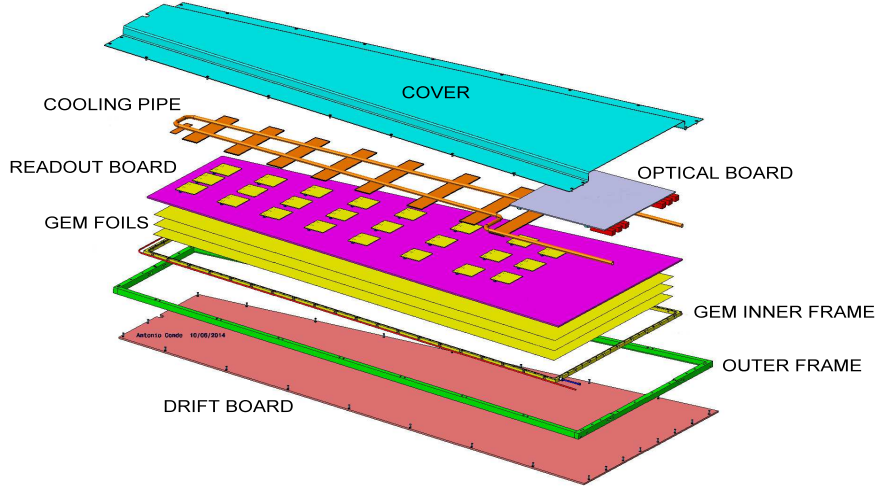


Figure 1.6: Several mechanical layers that build a GE1/1 detector [20].

conductor, whereas the GEM foil surfaces oriented towards the drift board are segmented along the height in small trapezoids with an area of $\sim 100 \text{ cm}^2$. Fig. 1.10 shows the segmentation of the GEM foil electrode and the HV lines that provide the powering of each segment. This segmentation in the first place reduces the surface eventually involved in a discharge, keeping the remaining 95% of the detector active. Furthermore, in the worst case scenario the damaging of one sector does not affect the integrity of the others, so the detector remains usable [20]. Fig. 1.7 shows the discharge probability for a small triple-GEM detector operated in the CMS GE1/1 configuration. Fig. 1.8 shows the rate capability, for the detector irradiated with an 8 keV X-ray source. The gain stays constant up to 100 MHz/cm^2 confirming that the GE1/1 chambers will easily operate in the $1.6 \leq |\eta| \leq 2.2$ of the forward muon system, where the expected rate is $\leq 10 \text{ kHz/cm}^2$.

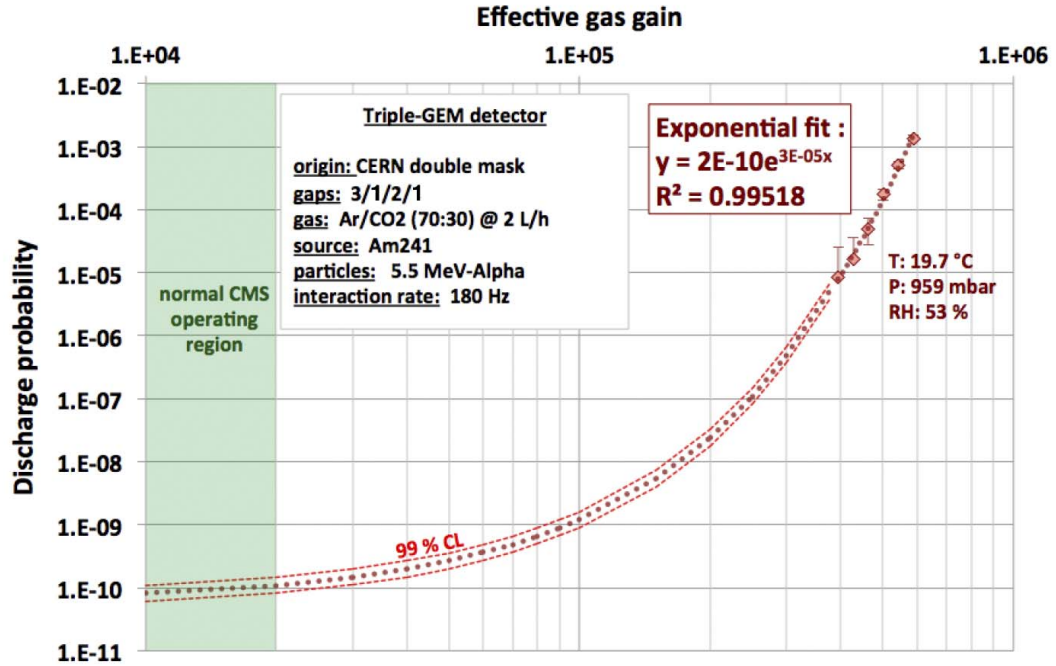


Figure 1.7: DischargeProbability

Discharge probability of a small triple-GEM detector in the CMS configuration. Discharges were triggered by mean of Highly Ionizing Particle (HIP)s at extreme gain. The discharge probability has then been extrapolated at lower gain [21].

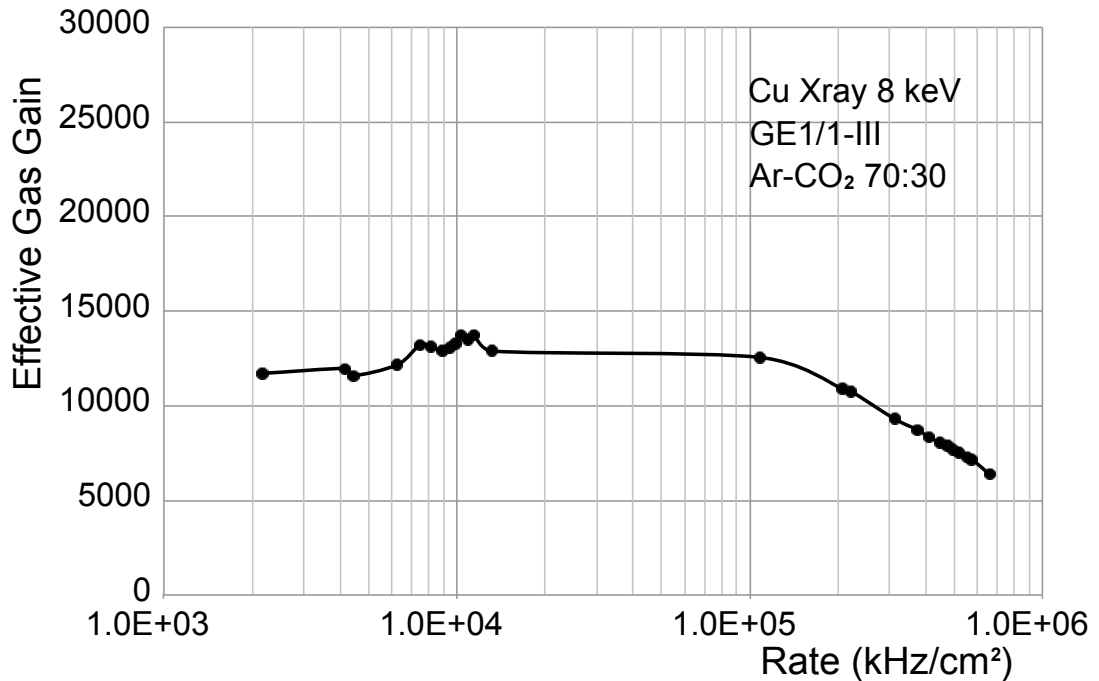


Figure 1.8: Effective gas gain as a function of the incident rate for an third generation GE1/1 prototype [20].

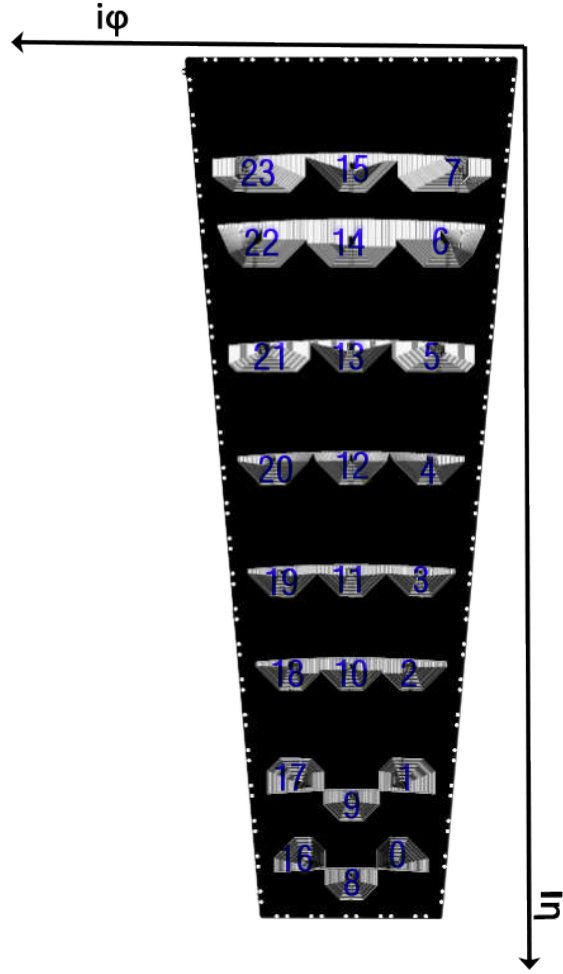


Figure 1.9: Segmentation of the readout board and the VFAT positioning with respect to $i\phi$ $i\eta$. Each VFAT reads the 128 strips relative to its partition.

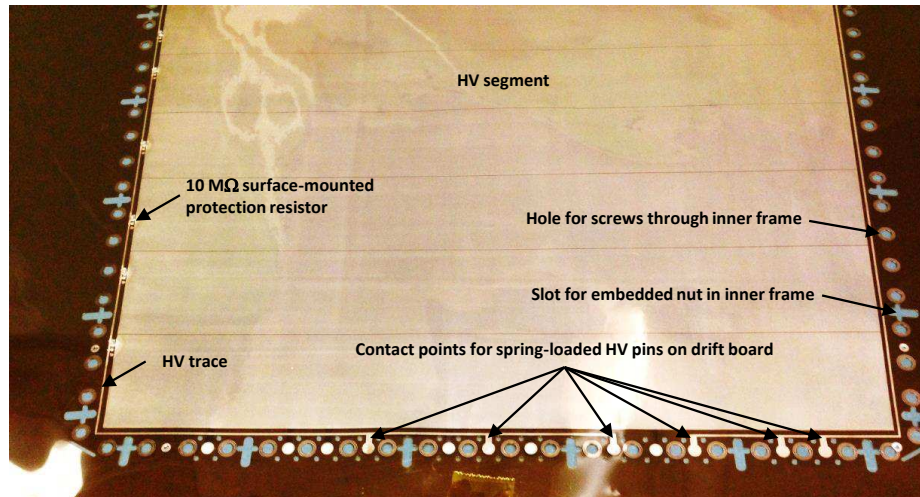


Figure 1.10: Segmentation of the GEM foil electrode that faces the drift board. Each segment has a surface of $\sim 100\text{ cm}^2$ and is powered through a $10\text{ M}\Omega$ resistor [20].

CHAPTER 2

Micro Pattern Gaseous Detector (MPGD)

Gaseous detectors have been largely employed in High Energy Physics (HEP) because of their versatility and their lower cost with respect to other technologies. In order to tackle the previous generation limitations, based on wire chambers, and to sustain the challenge of the modern collider experiment requirement, in the last decades a new generation of gaseous detectors has been developed, called Micro Pattern Gaseous Detector (MPGD). GEM detectors are an effective and mature MPGD representative, already installed in several HEP detectors and also to being installed in the CMS muon system. The first part of this chapter will describe three detector solutions that belong to the MPGD family, with a closer look on GEM and its implementations. In the second part there is a focus on one of the MPGD detector, the Triple-GEM.

2.1 Introduction to gaseous detectors

When a charged particle travels a medium, it dissipates energy mainly due to inelastic EM interactions, mediated by the interaction of the particle Coulomb field and the medium. The molecules of the medium acquire the released energy, resulting in an higher rotational or vibration states (if available), excited states or ionization, with the production of photons or electron-ion pairs [23]; the ionization process in gas, is commonly used in order to provide detectable signals. The Bethe-Bloch equation [24], and its further corrections, describes the energy loss from a charged particle that crosses a specif medium, due to multiple Coulomb interactions. Fig. 2.1 shows a comparison of the energy loss by protons and α -particles in a copper medium. For a given kinetic energy and medium, the higher is the mass or the charge of a particle, the higher will be the dissipated energy.

In a typical scenario, a charged particle of given energy, undergoes many scattering events with the electron cloud of the medium atoms, each of which dissipates part of its energy and may, or may not, free an electron-ion pair. Therefore an useful parameter to compare different gases, particle types and particle energies, is the

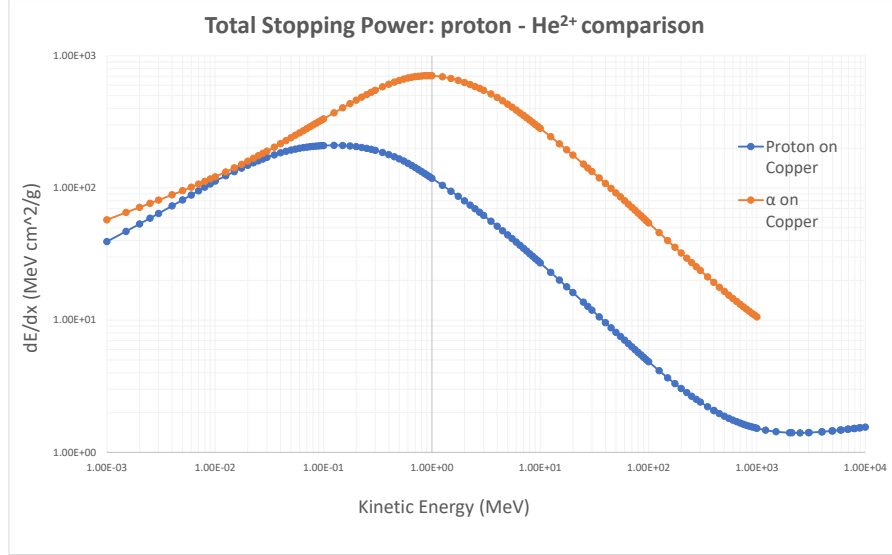


Figure 2.1: Stopping power comparison for protons and α -particles in copper. Data provided by [22].

average energy lost per electron-ion pair released the so-called W-value [25].

The photons can interact with matter by means of the EM force. The three main interactions are the photoelectric absorption, the Compton scattering, and pair production are the most exploited in the gaseous photon detection. In the photoelectric absorption and pair production the photon is destroyed after the interaction, therefore only one pair of charges can be freed in the gas for each photon. In the Compton scattering the incoming photon interacts destructively, therefore releasing an electron-ion pair and a new photon with different energy and direction. The charged particles dissipates their energy in multiple interactions with the medium, leaving a trail of electron-ion pairs on their track.

If no external forces act on the electron-ion pair, it can either recombine itself or diffuse in the gas, releasing its energy in collision with the medium. The presence of an external electric field instead, continuously provides momentum to electrons and ions. Appropriate values of the electric field can, in the time between two subsequent collisions, accelerate the electron as much as it is needed to ionize the gas and release a new electron-ion pair. The process can be iterated resulting in a multiplication of the primary released charge in an *avalanche*. If the electric field is increased, the total number of electron-ion pairs grows exponentially, until it reaches 10^7 - 10^8 known as the Raether limit. At this point, the spatial ion charge shields the external electric field, stopping the enlargement of the avalanche. Finally higher fields may trigger a spark breakdown, whose occurrence in is further detailed in Chap. 3.

Fig. 2.2 shows the major operating regime of a gaseous detector as a function of the applied electric field. The different gaseous detector technologies exploit

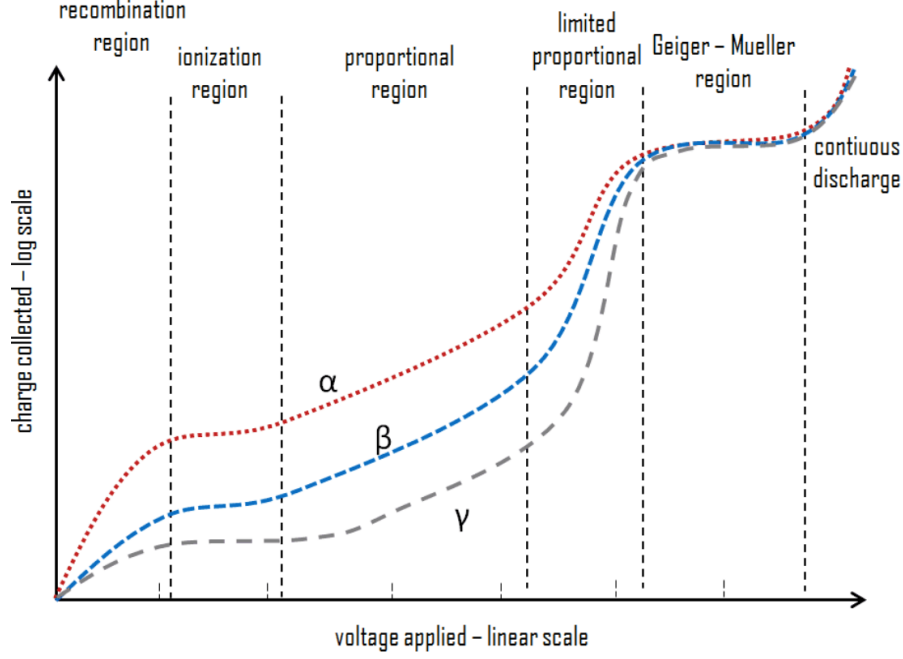


Figure 2.2: Multiplication factor for gaseous detectors as function of the electric field, for different radiations.

the physics process of multiplication at different electric field values, in order to find the best desing solution for a specific purpose. A detailed and comprehensive discussion about radiation detection in gasous detector can be found in [23, 25]. .

2.2 Overview of Micro Pattern Gaseous Detector (MPGD) family

The classical gaseous detectors, developed since early 1900, are relatively cheap and can be built in many shapes. Even though they have been developed over almost a century, they still have limitations that can should overcome. For example in a Multiwire Proportional Chamber (MWPC), invented in 1968, the spatial resolution is limited by the fact that distance between two wires cannot exceed a certain threshold, otherwise the high electric fields can easily rearrange the wires and consequently distort the field lines from its designed geometry. This will lead to a not reliable energy measurement and may also cause the breaking of the wires. Additionally, due to the mechanical constraints of such a wire, the maximum length is limited which does not allow to cover large detection surface. Furthermore the ion collection time is generally of the order of hundreds of μs , which limits the rate capability. Finally ageing problems have been observed, where a polymeric film was deposited on the wire (anode), reducing the gain of the detector and also affecting the noise.

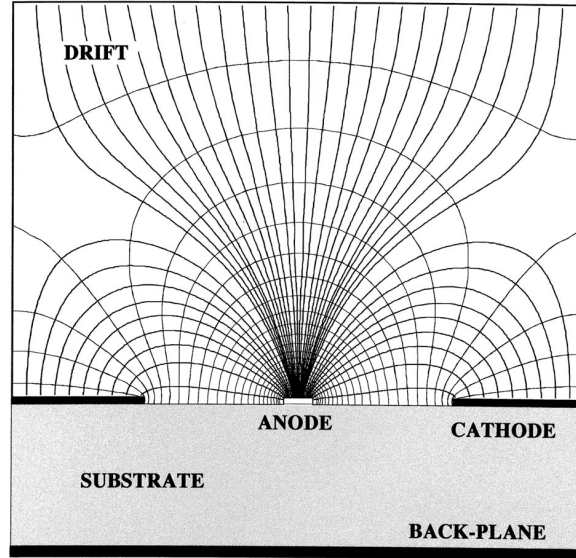


Figure 2.3: Electric field lines of a MSGC nearby the anode strip [23].

At the end of the 1980 a new generation of gaseous detectors were developed, called Micro Pattern Gaseous Detector (MPGD), in which primary ionisation and charge collection on one hand and the charge multiplication on the other hand, take place in a different region of the detector, speeding up the process of ion collection. MPGD detectors can also reach higher granularity with respect to classical gaseous detector, thanks to the photo-lithographic technique used for the electrode production. Three main categories of MPGD detectors are presented in the next paragraphs: the Micro-Strip Gas Chamber (MSGC), the Micro Mesh Gaseous Structure (Micromegas) and the Gas Electron Multiplier (GEM).

Micro-Strip Gas Chamber (MSGC)

The MSGC was developed by Oed [26] and are the first MPGD detector. It consists of a plane of strips, etched on a insulating substrate, that faces a drift plane. The strips are alternately anode and cathode, with anode strip width of the order of tens of microns, thus the electric field of a wire anode is replicated nearby these strips (see Fig. 2.3). In the gap between the two planes the incident radiation releases the primary electron-ion pairs which then migrate toward the anode strips. Only in the high field region nearby the anode surface the multiplication can take place. One of the advantages of MSGC with respect to MWPC is the higher rate capability, achievable thanks to the short path that the avalanche ions have to cover in order to be collected by the cathode, placed less then $100 \mu m$ away. Furthermore, thanks to the photo-lithography process that precedes the etching, the strips can be made with a narrow pitch, so that the spatial resolution is improved with respect to the MWPC. However, due to the small size of the region that

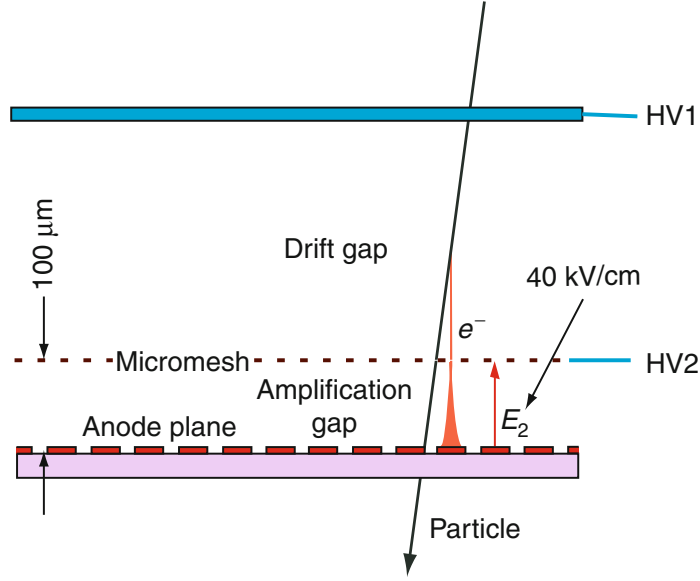


Figure 2.4: Sketch of a Micromegas layout and its working principle [27].

hosts the amplification and the intense electric field, discharges may be triggered which can damage the detector. Another potential issue is the charging up of the insulating substrate. The ions may in fact be collected by the substrate, and lead to a permanent surface charge that will ultimately distort the designed electric field in an uncontrollable way. A possible solution consists in a substrate with a finite electrical conductivity [25].

Micromegas

Micromegas have been proposed for the first time in early 1990 as an evolution of the parallel plate counters, with an amplification gap reduced to few hundreds of microns. Fig. 2.4 shows a sketch of the micromegas layout and the basic working principle. A micromesh structure divides the anode and cathode in two different working regions: the conversion and the amplification gap. The incident particle frees primary electron-ion pairs in the conversion region. Here the electric field is set by the ΔV between the cathode and the mesh, and while it causes the charges to drift toward the micromesh structure, it is not enough to multiply the charge. The micromesh is nearly transparent to electrons, so $\simeq 95\%$ of them can reach the amplification region where the set electric field supports the formation of an avalanche. Typical gain values are between 10^3 and 10^4 while the space resolution can be better than $100 \mu m$. The gap between the strips and the micromesh is $\simeq 100 \mu m$, therefore the ions released during the avalanche can be quickly collected. The small multiplication gap also allows to have fast collection of the electrons, resulting in a time resolution of the order of 5-10 ns. This small gap is achieved by means of insulating pillars that hold the mesh. Even if the spacing between the

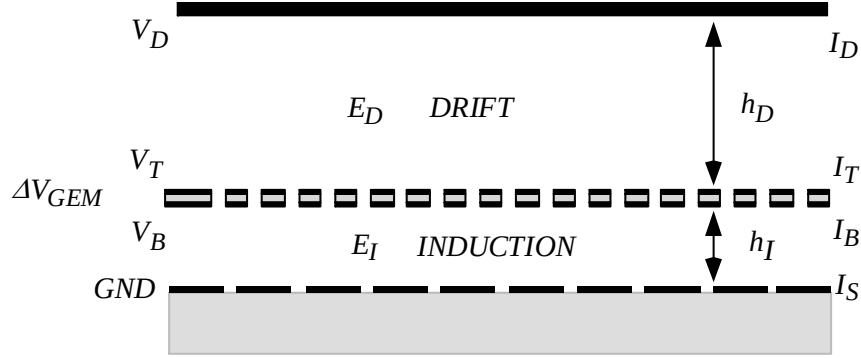


Figure 2.5: Sketch of a GEM layout [28].

mesh and the strips is not uniform, the electric field increases where the distance decreases and vice-versa, granting a uniform multiplication factor.

Gas Electron Multiplier (GEM)

In the GEM detectors, the amplification, the drift and the signal induction region are separated. Fig. 2.5 shows the layout of a GEM detector. The drift plane is facing a thin polymer foil (typically $50\ \mu\text{m}$) of insulating material (often kapton) with both surfaces covered with a conducting metallic cladding; a fine pattern of small holes through the foil is then produced through chemical etching [25]. By applying appropriate voltages on the drift plane and on both sides of the foil, the electrons produced by the incident radiation in the drift gap, are attracted by the holes. Here the electric field allows the multiplication and drives the electrons toward the induction gap. The ions are mostly collected by the top side of the foil, while the bottom side of the foil collects part of the electron cloud generated in the holes. This causes a difference between the total gain (electrons produced in the hole) and the effective gain (electrons seen by the strips). The most common GEM foil is made by a $50\ \mu\text{m}$ thick polymer layer, with $5\ \mu\text{m}$ layer of coating copper and hole diameters between $50\text{--}100\ \mu\text{m}$. Such a geometry is the result of an optimization process that has reached gain values up to few thousands. GEM detectors have demonstrated rate capabilities up to $100\ \text{MHz}/\text{cm}^2$ [25], many orders of magnitude higher than the one obtainable with the MWPC.

2.3 Triple-GEM detectors

The separation between the drift, the amplification and the signal induction region is one of the great advantages of a GEM detector. In fact it allows a modular implementation, with multiple amplification stages interleaved by transfer gaps, in

which the electrons are driven toward the next amplification stage. By sharing the amplification of the charge between several stages, a large amplification factor can be reached, without even getting close to the Raether limit. As a rule of thumb, a multiplication factor of 10^5 can be reached by using three amplification stages with a gain of $\sqrt[3]{10^5} = 46$. Therefore is possible to operate the detector at a lower electric field and lowering the probability of discharges while maintaining a good amplitude of the induced signals. Indeed the triple-GEM detectors are widely used in HEP and have also been chosen for the upgrade of the CMS muon system in the GE1/1 station. The transfer gap heights and the powering voltages are crucial parameters for the detector performances. In particular one wants narrow gaps and high transfer fields in order to extract electrons from the holes and avoid the charge diffusion. At the same time a 2-3 mm drift gap is needed to ensure an high detection efficiency due to the higher yield of primary electrons. An optimum solution foresees 1-2 mm and 3 mm for the transfer and the drift gap respectively, with a transfer field of 3-5 kV/cm. A gap configuration is commonly written with the gap height in mm starting from the drift to the induction gap (i.e. 3/2/1/2). Finally, not all the produced electrons will reach the induction gap. Some of them will be absorbed by the GEM foil electrode or recombine with the ions. For this reason one usually refers to *absolute* and *effective* gain. The former is related to the multiplication factor of the avalanche, the latter is related to the actual number of electrons that reach the anode electrode. Thus, the detector effective gain has to be measured. Usually X-ray photons are used and the effective gain is measured as:

$$G_{eff} = \frac{I_{anode}}{N \times R \times e} \quad (2.1)$$

I_{anode} is current that is produced on the anode, N is the number of primary electrons released by the X-ray photon in the drift gap, R is the X-ray source rate and e is the electron charge. Fig. 2.6 shows a comparison for the effective gain between a single a double and a triple-GEM.

2.3.1 Early Triple-GEM detectors

Triple-GEM detectors have been operated in many high energy physics experiments.

In the COMPASS experiment [30], 11 triple-GEM stations were instrumented as a part of the small area trackers. The gap configuration was 3/2/2/2 for a typical gain of 8×10^3 in Ar/CO₂ (70 : 30). The COMPASS experiment was the experiment which adopted triple-GEM for the first time in a high-intensity particle beam [30]. The Large Hadron Collider beauty (LHCb) experiment [31], installed triple-GEM detectors in order to fulfill the 500 kHz/cm² requirement for the innermost detectors of the first muon station. The gap configuration is 3/2/1/2 for a gain of 6×10^3 in Ar/CO₂/CF₄ (45 : 15 : 40) and a time resolution down to few ns [31]. The Total

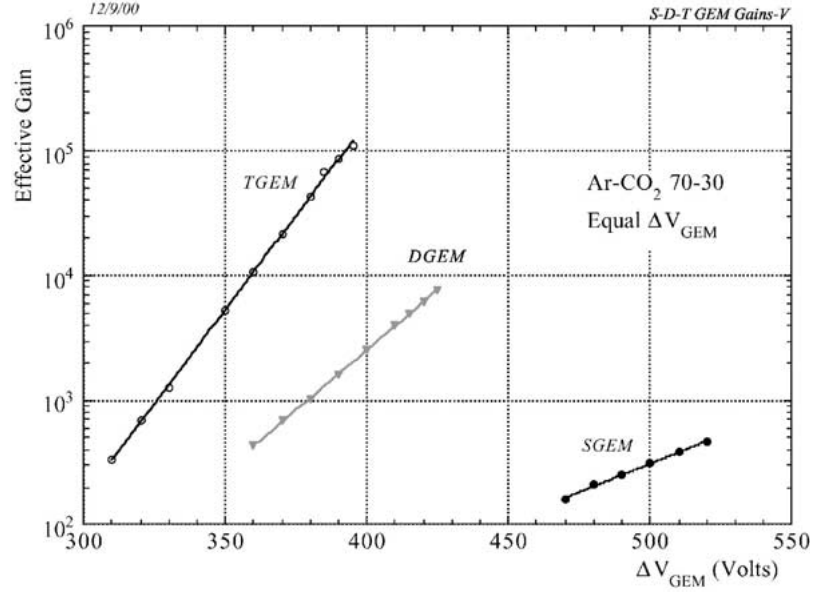


Figure 2.6: Effective gas gain for single double and triple-GEM [29].

Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC (TOTEM) installed triple-GEM detectors in the TOTEM forward telescope T2. Each arm of the telescope were equipped with 20 semi-circular triple-GEM detectors [32]. The designed electric field is 3.6 kV/cm in the drift and 2.4 kV/cm for the three transfer, while the effective gas gain is approximately 8×10^3 [32]. TOTEM GEM used VFAT2 as a front-end electronics, which has been lately used in the GE1/1 *Slice Test*.

CHAPTER 3

Discharges studies on gaseous detectors

As we have seen in the gain as a function of the applied voltage diagram (Fig. 2.2, p. 17), the gain of a gaseous detector rises proportionally with the applied voltage, until it switches to *discharge mode*, when a threshold voltage is exceeded. Thus, the achievable values for gas gain are limited by the discharge process. Furthermore if, for whichever reason, the electric field inside a gaseous detector is locally distorted, discharges may be triggered in the safe voltage operational range, with hazardous consequences for the detector structure.

In this chapter a summary of the current knowledge on discharges in gases is presented. The first part is dedicated to a general description of the discharge formation process, starting from the avalanche to the spark formation adapted from [35, 34, 33], while specific studies on discharges in GEM detectors are presented in the second part.

3.1 What is a discharge?

The process of *gas discharge* refers to the electric flow through a gap of gas, turning the insulating gas into a conductor [35]. Originally it was associated with the discharge of a capacitor into a circuit incorporating a gas gap between electrodes: when a sufficiently high voltage is applied, the gas forms a ionized state and so allows the flow of current, therefore the capacitor discharge. Later on, the term *discharge* was applied to any flow of electric current through ionized gas [34].

The discharges can be classified in two main groups, according to the properties of the electric field: *DC discharges* and *AC discharges*. Since the applied electric field inside a gaseous detector is static, the DC discharges are of primary interest for our purposes. DC discharges, are further classified in non-self-sustaining and self-sustaining. The former are characterized by an electric current that survives only while a source of primary electrons is maintained. As the electric field is increased, the electric current induced by a non-self-sustaining discharge increases as well thanks to the enhanced force on the charges that avoids recombination.

Beyond a certain electric field value the electric current that flows through the gas, sharply increases and is maintained even when the source of primaries is removed, thus resulting in a self-sustaining discharge.

When the gas is operated at low pressure (≤ 50 Torr) and the induced current is limited by a resistor, a *glow discharge* develops. This is commonly exploited in the commercial Neon lights for advertisements. For higher values of the gas pressure (~ 760 Torr - 1 atm) and no limitation on the current, an *arc discharge* develops. Arcs produce an higher current with respect to glow discharges, even higher than 1 A. At the atmospheric pressure, the arcs usually form plasma in thermodynamic equilibrium, in which the temperature of the gas reaches $T \sim 10^4$ and a fraction $x = 10^{-3} \div 10^{-1}$ molecules is ionized [34]. The arc discharge extracts electrons from the cathode, which is crucial for the self-maintenance of the current. The process is driven by the thermionic emission on the cathode surface, where the heat is delivered by the high current that heats up the cathode. In the same conditions, if the electric field is further increased, *sparking* occurs with the development of a plasma channel between the two electrodes. Thus they result to be short-circuited. These last two types of self-sustained discharge are the typical processes that can be triggered in gaseous detector.

3.1.1 Single electron avalanche

The following paragraphs describes the development of the avalanche started from a single electron; the approach is based on [34]. Firstly let us consider a single electron that leaves the cathode at $t = 0$, and drifts in an uniform external field E_0 . Additionally let us take the x-axis starting from the cathode toward the anode, and denote r the radial distance from the x-axis. Let us assume that the ionization of the gas (produces one electron-ion pair) and the electron attachment (absorbs one electron and produces one negative ion), are the only processes that affect the number of electrons N_e . The following equations arise:

$$dN_e/dx = (\alpha - a) N_e, \quad dN_+/dx = \alpha N_e, \quad dN_-/dx = a N_e \quad (3.1)$$

where α and a are the ionization and attachment coefficient respectively, while N_e , N_+ , and N_- are the total number for electrons, positive ions and negative ions. While electrons diffuse, ions can be considered as static due to their 2-3 order of magnitude smaller velocities. Therefore, the charge density for each of the three species is described by differential equations close to the Eq. 3.1, except for an additional diffusion term in the electron equation. By neglecting the attachment, an approximate calculation for the positive ion density reads:

$$n_+(x, r, t = \infty) = \frac{\alpha}{\pi r_D(x)^2} \exp\left(\alpha x - \frac{r^2}{r_D^2(x)}\right), \quad r_D(x) = \sqrt{\frac{4D_e x}{\mu_e E_0}} \quad (3.2)$$

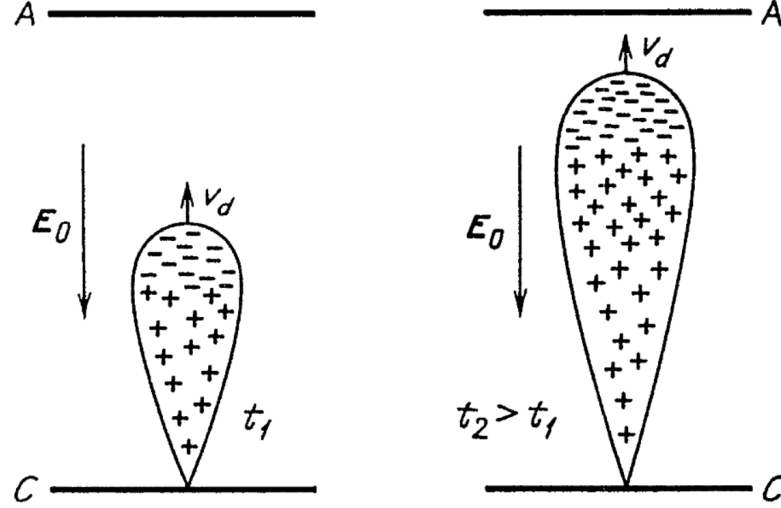


Figure 3.1: Sketches of the charge distribution of an avalanche started at the cathode for two subsequent instants. E_0 and v_d are the external electric field and the electron drift velocity respectively [34].

where D_e is the diffusion coefficient for electrons and μ_e their mobility, whereas r_D is the radius at which, due to the diffusive process, the electron density decays by a factor $1/e$ with respect to its value at $r = 0$.

Eq. 3.2 states that the ion density along the avalanche trail increases exponentially, following the law of charge multiplication. In the radial direction instead, the ion density decays with the same Gaussian law that describes the electron density, although it is due to production reasons rather than the diffusive process. We can obtain the spatial occupancy of the ion side of the avalanche by requiring that the exponent in Eq. 3.2 approaches zero: $r_i = r_D(x)\sqrt{\alpha x} = \sqrt{\frac{4D_e\alpha}{\mu_e E_0}}x$. Therefore the shape of the ion side of the avalanche is conical, that becomes spherical in the electron region (head) of the avalanche. Fig. 3.1 shows a sketch of the avalanche shape and charge distribution in two subsequent instants.

Space charge contribution

The space charges developed in the avalanche, build up the electric field E' that has to be added vectorially to the external E_0 , and that leads to field distortion in the vicinity of the avalanche. The higher velocity of electrons leads to the formation of a sort of dipole, where the electrons are mostly at the head of the avalanche, while the positive ions, that have velocities smaller by a factor 100-1000, stay behind. As the distortion increases, the contribution of E' in the resulting field $E = E_0 + E'$, becomes relevant, therefore the charge distribution rearranges and thus affects the distortion field E' . These processes are described by a set of simultaneous equations for the field that are difficult to solve. Fig. 3.2 shows a qualitative representation

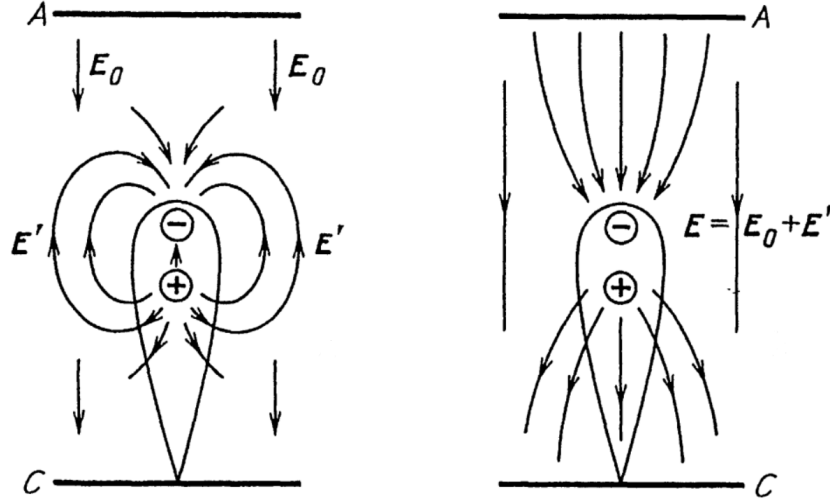


Figure 3.2: On the left the external electric field E_0 and the one due to the space charge E' during the developing of a discharge. On the right their vectorial sum [34].

of the field during the avalanche. The space charges field E' is opposite to E_0 in between the electrons and ions, resulting in a lowered overall field E , while they sum up in the head and the tail of the avalanche.

3.1.2 Townsend discharge theory

The first work on the theory of break down in gases, which constitutes the foundations of the current knowledge about discharge in gases, was carried out by Townsend [36]. Townsend considered the parallel plate chamber model to perform an evaluation of the number of electrons collected at the anode. By assuming that α and β are the number of ionizing event per unit length for electrons and ions respectively, that l is the gap height and n_0 is the number of primary electrons released in correspondence of the cathode electrode, he deducted the number of electrons that reach the anode:

$$n = n_0 \frac{(\alpha - \beta) \exp [(\alpha - \beta) l]}{\alpha - \beta \exp [(\alpha - \beta) l]} \quad (3.3)$$

where α and β depend on the electric field. As the distance between plates approaches $l_c = \frac{1}{\alpha - \beta} \log \frac{\alpha}{\beta}$, n positively diverges, which indicates that the electrons would continue to reach the anode even if no more primaries n_0 are released in the gas. This first attempt to explain the electric break down of the gas, assumes both electron and ion as avalanche generators. However, by taking into account the velocities for both avalanches types, this mechanism fails in the prediction of the time scale for the development of a discharge, which was measured to be 2 – 3 orders of magnitude faster than predicted.

3.2 Streamer

The improvements in the experimental techniques, equipment, and in the methods of analyzing the fast processes involved in a discharge, allowed the emerging of new evidence. For example, any contribution of the electron extraction from the cathode electrode to the discharge, was ruled out because of the longer time scale of these processes and for the independence of the breakdown voltage on the material of the cathode. A new theory of spark breakdown was developed, based on the studies of Raether, Loeb and Meek [38, 37]. The basic idea was the growth of a ionized channel, called *streamer*, between the anode and the cathode. A streamer can be formed from the primary avalanche if the electric field is strong enough, whether it is the external one or the one built by the space-charge of electrons and ions. Since the ions are static compared to the typical electron speeds, the streamer follows the ions trail left behind by the primary avalanche. If new avalanches are initiated close to the positive ions trail, they are pulled into the trail by the field.

3.2.1 Raether theory for streamer

The studies carried out by Raether [38], established a critical number of charge of $N_c \sim 10^7$ above which the electron avalanche becomes unstable and presented a reasonable interpretation for the process. Raether also observed that the streamer develops toward the anode at $\simeq 8 \times 10^7$ cm/s in air at $E/p \simeq 40$, while the electron drift velocity in similar condition was measured to be $\simeq 1.3 \times 10^7$ [39]. A little later a track starts to develop also toward the cathode; if it reaches the cathode, the two electrodes are connected and, as a consequence, an high intensity flash of light is produced, named *spark*. In case a certain gas mixture would not produce visible light, this would still be a spark and you would still hear a *clack*. The following arguments make it possible to explain propagation velocities greater than the electron speed in the gas; furthermore the high velocities measured also for the growth of the cathode track [38], can be explained, likewise, with the photo-electrons produced by radiation.

Let us take into account the development of the discharge toward the cathode and let us use the numeric model developed by Raether in [38], in which further details can be found. Since the anode track has already been developed on the anode side, the recombination of charges, the bremsstrahlung emission and the atoms de-excitation produce energetic photons, which, amongst other thing, release photo-electrons in the gas gap. While the photo-electrons produced far from the avalanche development axis lie in a feebly distorted electric field (see Fig. 3.2), the photo-electrons released in front of the avalanche tail, sense an electric field greater than the external one. Thus, the enhanced electric field carries out the multiplication and so the cathode directed streamer is initiated. In the early stage of

avalanche formation, we can approximately model its head (tail) with a negatively (positively) charged space-charge sphere of radius ρ . Let us assume that at the time t_0 a photo-electron is released at a distance 2ρ from the ions sphere toward the cathode. Also, let us assume that, since the spatial charge of both spheres distorts the electric field, at the border of the ion sphere that faces the cathode the electric field is ten times higher than the original one. At $t \geq t_0$, the photo-electron will start to migrate toward the positive space-charge sphere, and to be multiplied by ionizing collisions with the gas. After migrating for $\Delta x = 0.3\rho$, the multiplication has produced enough positive charges to reproduce the electric field that existed at t_0 at the border of the ion sphere that faces the cathode. Therefore the ions border has advanced $(2\rho - \Delta x) - \rho$, and the ratio between the rate of development of the cathode avalanche and the speed of the electrons is:

$$\frac{v_{aval}}{v_e} = \frac{(2\rho - \Delta x) - \rho}{\Delta x} = 2.3 \quad (3.4)$$

thus avalanches can be *faster* than the electrons if we take into account the radiation contribution. This calculation does not take into account the recombination, the actual spatial distribution of the charges nor the exact electric field geometry. However it provides a reasonable explanation for the streamer mechanism and suggests that two main topics involved in the description of a discharge are the creation and the motion of charges. Fig. 3.3 summarizes the development of the streamer. The formation of anode directed streamer is governed by a similar mechanism; however, since the streamer and the electrons travel in the same direction, the secondary avalanches are produced in front of the negative head of the streamer. Thus the resulting electric field on the head of the streamer is the sum of the external field E_0 and the electric field produced by the ions left behind by the secondary avalanches E_I . Therefore the streamer front electrons can join the positive tail of secondary avalanches accelerating the development of the streamer.

3.2.2 Streamer inside a GEM hole

In order to start a streamer inside a GEM hole, the electric field distortion due to the ion space charge has to sum up with the external field and the result has to be high enough to achieve gas amplification in the vicinity of the avalanche. Therefore the total amount of electrons produced has to overcome a threshold value. An estimation of the order of magnitude of this threshold is evaluated in [40]. Following the same approach, we can assume that the charge is mostly produced at the bottom of the hole, due to the exponential trend of the multiplication; additionally all the electrons will leave the region much faster with respect to the ions, that are the only charges that will provide the distortion field. If we assume the ions to distribute in a sphere of radius $R = 20 \mu\text{m}$ and consider that in Ar-CO₂ (90:10) the

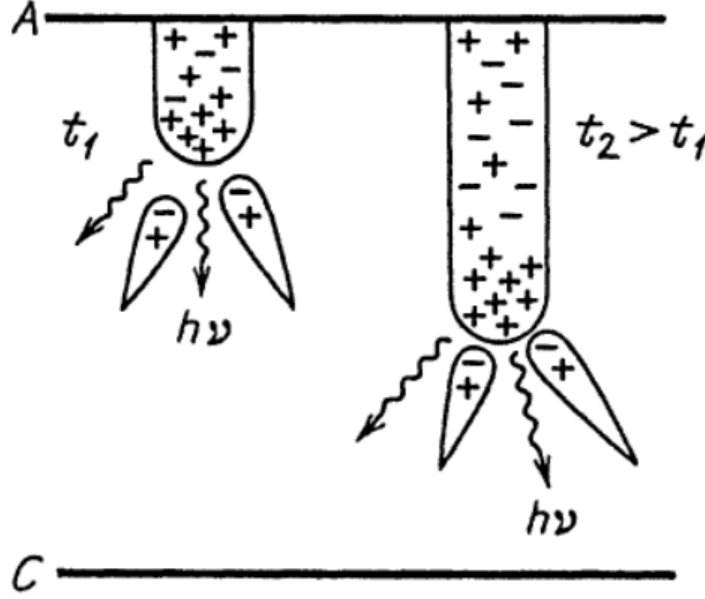


Figure 3.3: Two consecutive moments of time in the development of a cathode streamer. The secondary avalanches, triggered by the photo-electrons, emit additional photons that free electrons that triggers more secondary avalanches.

gas amplification starts at $\sim 10 \text{ kV/cm}$ then it results:

$$E_0 + eN_e/(4\pi\epsilon_0 R^2) = 10 \text{ kV/cm} \quad (3.5)$$

Since the electric field is evaluated on the border of the ion sphere, located at the end of the hole, the external field can be neglected giving $N_e \sim 3 \times 10^6$. Therefore the condition for the formation of the streamer is met earlier than the Raether limit. This evaluation suffers of many approximations, such as the spherical distribution of the ions and the contribution of the external field. However the order of magnitude is confirmed by experimental result [40].

3.3 Spark channel

The initial streamer channel may increase rapidly and with it the degree of ionization in the area increases as well. If the streamer connects cathode and anode, it can initiate a *spark* between the two electrodes. The spark channel is referred as a strongly ionized plasma, that is highly conductive and is visible by eye and is followed by a typical sound. The sound is originated by the *shock wave*: the flow of an high discharge current releases a large amount of heat and increases the gas temperature; the subsequent sharp rise in the gas pressure is responsible for the shock wave, resulting in the typical discharge sound (*lightning* can be taken as an example: it is a spark in the air on a large scale). It should be noticed that

streamers allow the flow of typical current of the order of 10^{-2} A, while for a spark channel it can easily reach $\gg 1$ A.

3.3.1 Spark development

There is not yet a solid and commonly accepted theory on the formation of a spark channel, Raizer in [34] describes a qualitative picture that summarizes the current knowledge. Even if the streamer is a weakly conducting channel, the potential of the front of the cathode-directed streamer, is very close to the anode value when the anode-directed streamer is contacting the anode. Therefore, as the streamer develops toward the cathode, the ΔV between the electrodes falls in the gap between the cathode-directed streamer and the cathode. This speeds up the streamer process until it contacts the cathode. The intense electric field multiplies the photo-electrons at enormous intensity and the electrons accumulated on the cathode due to the positive space-charge of the streamer, propagates toward the anode along the channel of the streamer. The result is a *reverse streamer* that grows from the cathode to the anode, producing an high ionized plasma. When the reverse streamer reaches the anode it connects the electrodes and the the formation of a spark channel is reached. The radius of the spark channel increases up to $r \sim 1$ cm and the maximum current can reach 10^4 A, for a current density of $J \sim 10^4$ A/cm². The heat released due to the Joule effect increases the ionization and the temperature in the spark channel can reach 20000 K. The conductive channel between the electrodes quickly reduces the voltage difference between them until the spark is extinguished.

The large amount of current and heat that are released in a spark channel can damage the mechanical integrity of the microscopic pattern of a MPGD detector and result may affect the detection performance. Additionally the large amount of current could literally burn the front-end electronics. Fig. 3.4 shows the strips of a MSGC damaged by spark discharges.

3.4 Discharge studies on GEM detectors

In this section are presented the latest studies carried out on GEM detectors. When the GEM detectors are operated at high gains or highly ionizing particles, a discharge may be triggered inside the GEM holes. Occasionally this event may be propagated in another GEM foil or toward the anode. The GEM foil results to be robust to discharge and can sustain hundreds or thousands of discharge without affecting its performances. Several groups have studied the process of discharge propagation toward the anode, primarily to mitigate the propagation to the anode where the connected readout electronics can be severely damaged. I will present

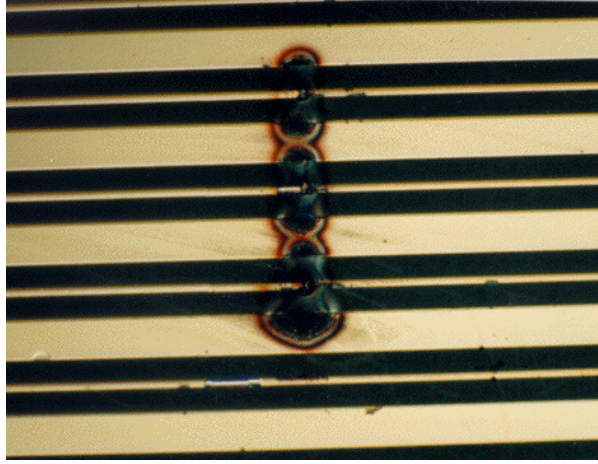


Figure 3.4: Image of the electrodes of a MSGC, damaged by discharge triggered between the cathode strip (wider) and the anode strip (narrower) [41].

the state-of-the-art knowledge based on discharge studies described in [29, 42, 40, 43, 44]

3.4.1 Discharge propagation between GEM foils

As already stated in the Sec. 2.3, in most applications double or triple GEMs are preferred to single GEM, due to their lower electric field at each stage. Fig. 3.5 shows the discharge probability for single, double and triple GEM detectors as a function of the effective gain. The electric field needed to achieve a given gain decreases as the number of GEM foil is increased, ensuring a much lower discharge probability as the number of amplification stages is increased.

The discharge inside the GEM hole, where the electric field is of several tens of thousands of kV/cm, can also propagate from one foil to another (in double and triple-GEM detectors) or even to the readout plate. In the studies presented by Peskov [42], it was found that the discharge propagation between GEM foils is independent from the transfer field between them; additionally, the propagation of this discharge, has been observed even when the transfer field between two adjacent GEM foils, is reversed. For transfer gap on the *mm* order of magnitude (comparable with the ones in GE1/1 triple-GEM), the discharge can propagate also backward: it has been observed that a discharge that starts in the second GEM and propagates to the first GEM. Another study conducted by Deisting et al. [40] on a double-GEM setup, highlights simultaneous discharges in both foils within a time of 10 ns. Since the transfer gap was 2 mm thick, the interpretation of this process can not rely on the migration of charges between one foil to the other. Only a photon driven mechanism remains reasonable. In fact, also the streamer driven mechanism can be ruled out, since the transfer field between the gap, about 5 kV/cm is not enough to

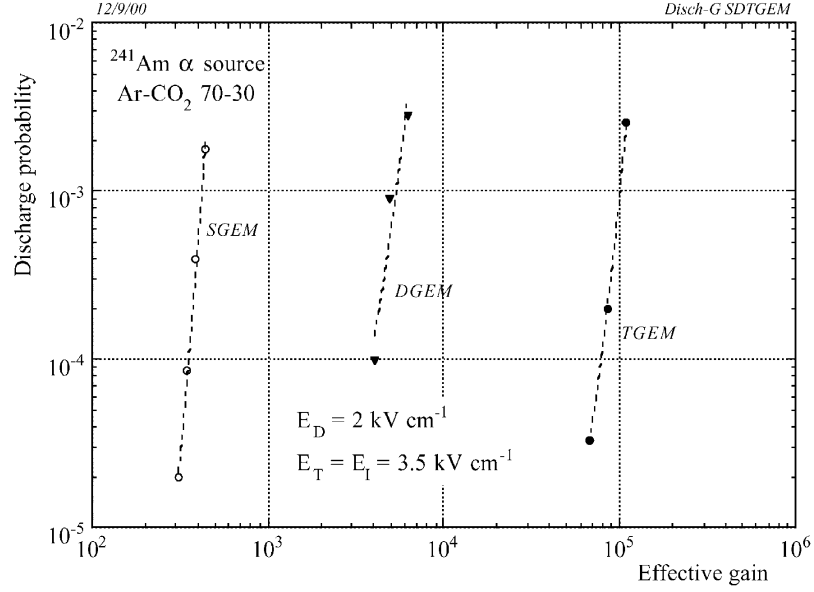


Figure 3.5: Discharge probability as a function of the effective gain for single, double and triple GEM detectors operated in Ar-CO₂ [29].

sustain the streamer formation.

3.4.2 Discharge propagation toward the anode

The discharges triggered in the GEM holes can propagate to the anode, where the readout electronics are located. It differs from the discharge propagation between GEM foils, because it happens on longer time scale [29]. However this is a much undesired process, as it may lead to permanent damages of the front-end electronics. In the GEM foil instead, discharge induced short-circuit may be recovered by applying an over voltage on the GEM electrodes.

The discharge propagation probability in the induction gap, depends on the induction field and on the energy of the primary discharge, while is almost independent from the transfer field between the GEMs [29]. Surprisingly adding a parallel external capacitor to the induction gap, increases the propagation probability: the reasons for this behavior have not been understood. Fig. 3.6 shows the propagation probability as a function of the induction field, for different values of the capacitance added in parallel to the induction. This effect leads to differences in the discharge propagation probability between small and large surface detectors, and has been also observed during the operational experience detailed in the Chap. 4, .

In [43] is presented a study on the discharge propagation toward the anode. A single $10 \times 10 \text{ cm}^2$ foil with large hole pitch was instrumented on a frame with a 2 mm thick induction gap. An high speed camera was used in order to correlate the voltage signal from the electrodes with the optical view of the inside of the

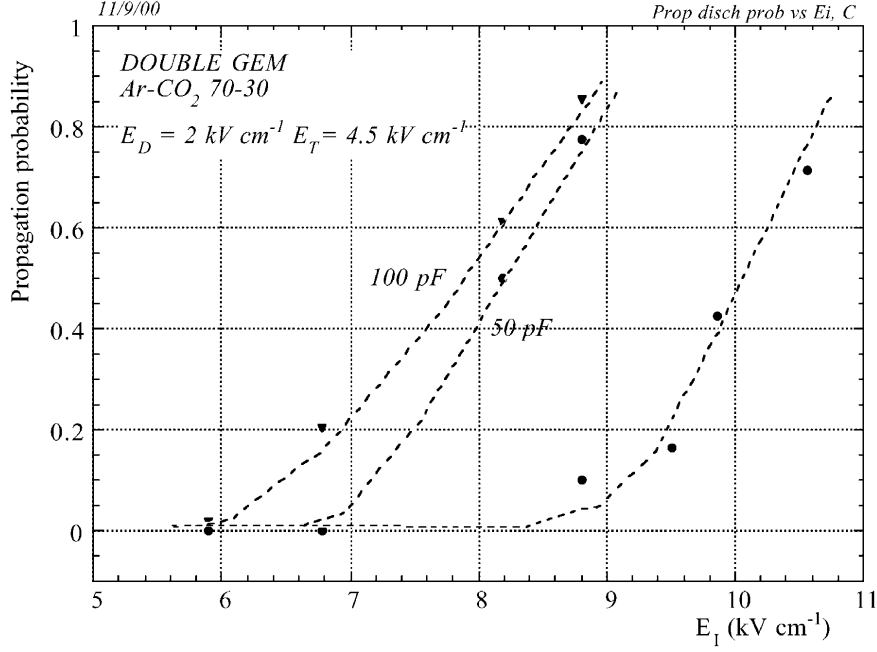


Figure 3.6: From left to right the discharge propagation probability for 100 pF, 50 pF and 0 pF of additional capacitors added in parallel with the induction gap [29].

chamber. The mixture used was Ne-CO₂-N₂ (85 – 10 – 5). Fig. 3.7 shows the time development of the voltage on the GEM foil electrode and on the readout, together with a photograph taken by the high speed camera triggered on the GEM hole discharge (from now on referred as primary discharge). The picture on top, shows the development of a primary discharge, while on the bottom one, a secondary discharge is triggered 80 μ s later with respect to the primary discharge. The secondary discharge photograph, highlights the formation of a streamer in the induction gap. Even more interesting is the pattern on the foil electrodes voltage soon after the secondary discharge. It is interpreted as a multiple re-ignition of the secondary discharge in the induction gap, that induces a large amount of current on the read-out. Each time that a discharge occurs in the induction gap, the GEM bottom electrode drops toward zero, hence it is short-circuited with the anode electrode. This is a strong evidence of the development of a spark channel between the GEM bottom electrode and the anode. While the primary discharge induces a positive current on the anode, the current induced by the secondary discharge is negative and can be interpreted as the flow of the ions toward the anode through the spark channel in the induction gap. The readout current follows three main regimes. Firstly there is the primary discharge signal, that induces a large amount of charge on the readout electrode followed by a slow decay, attributed to the migration of the ions toward the bottom GEM electrode. The thermionic emission causes the second

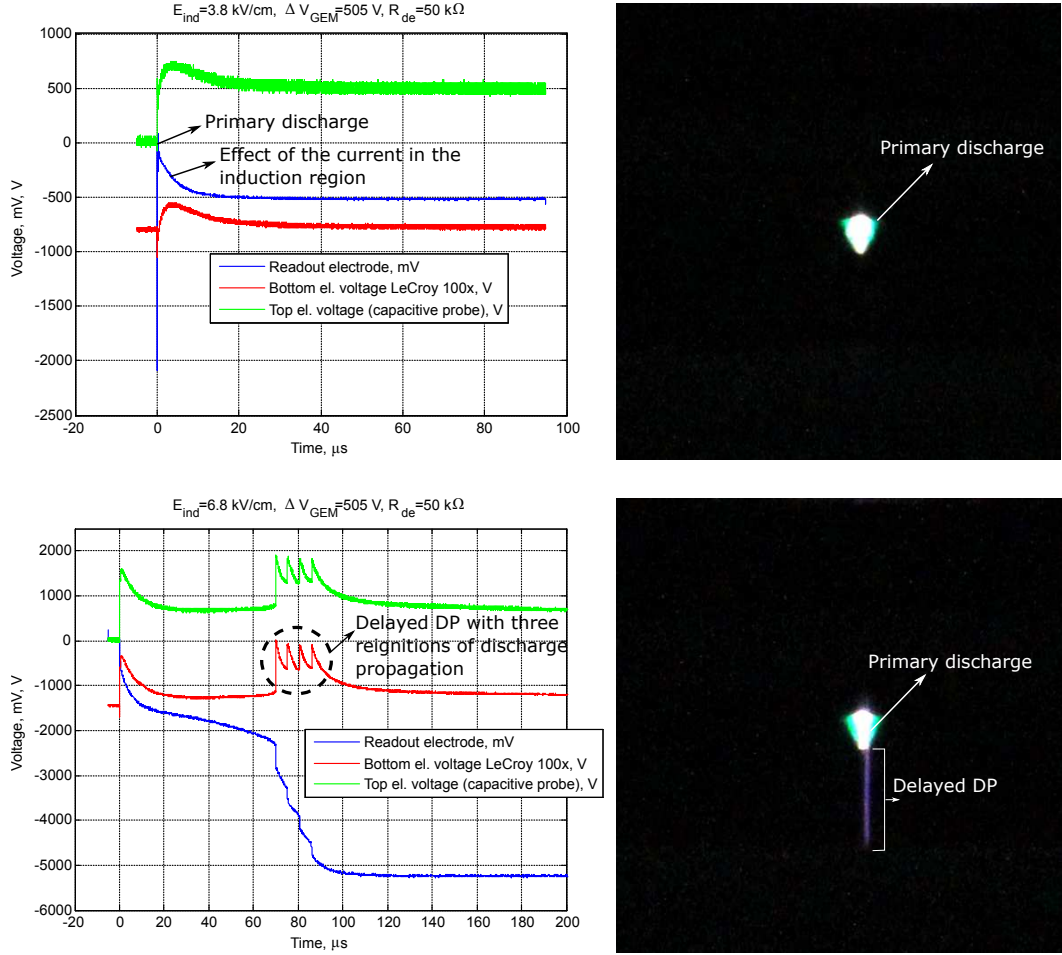


Figure 3.7: The recorded oscilloscope data and the simultaneously high speed photograph from a propagated discharge. The induction field is 6.8 kV/cm , the decoupling resistor $R_{de} = 50 \text{ k}\Omega$. The camera is triggered on the primary discharge [43].

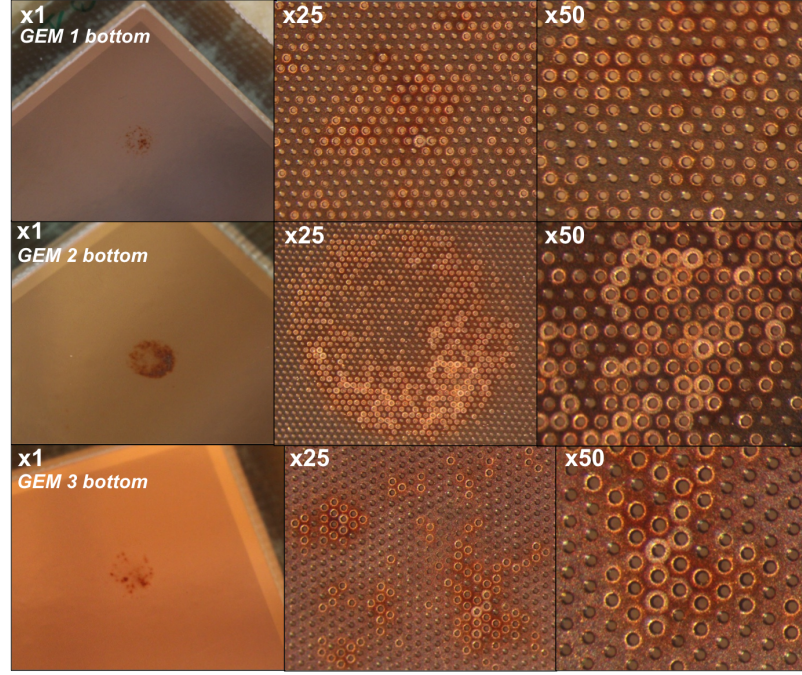


Figure 3.8: Microscopic views of the bottom layers of the three GEM foils after a total of 450 discharges accumulated [21].

anode current main regime, which is a constant current of about ~ 1 mA. The third and last anode current regime consists in a sharp rise that precedes the gas breakdown of the induction gas gap. The interpretation of secondary discharges proposed in [43] is based on the thermionic emission. The primary discharge heats up the GEM bottom electrode and thus the induction electric field is sufficient to stimulate the thermionic emission in the induction gap. The thermionic current can eventually increase and thus lead to a discharge in the induction gap. The thermionic driven mechanism can justify the delay of tens of μs between the primary and the propagated discharge. Finally the copper melted droplets observed on the GEM hole rim after the discharge (see Fig. 3.8 and Fig. 3.9), indicates that a large amount of heat is released during the primary discharge and this can sustain the thermionic hypothesis.

High voltage scheme optimization

Recently, a study on the influence of the high voltage scheme on secondary discharges, was carried out [44]. The results suggest that the capacitance of the induction gap should be kept as low as possible in order to avoid discharge propagation. The induction field was confirmed to be the key parameter that regulates the propagation. Additionally the decoupling resistor on the GEM bottom electrode, is a crucial factor to avoid propagation. In fact, the streamer current that precedes the propagation, induces a voltage drop on the decoupling resistor and

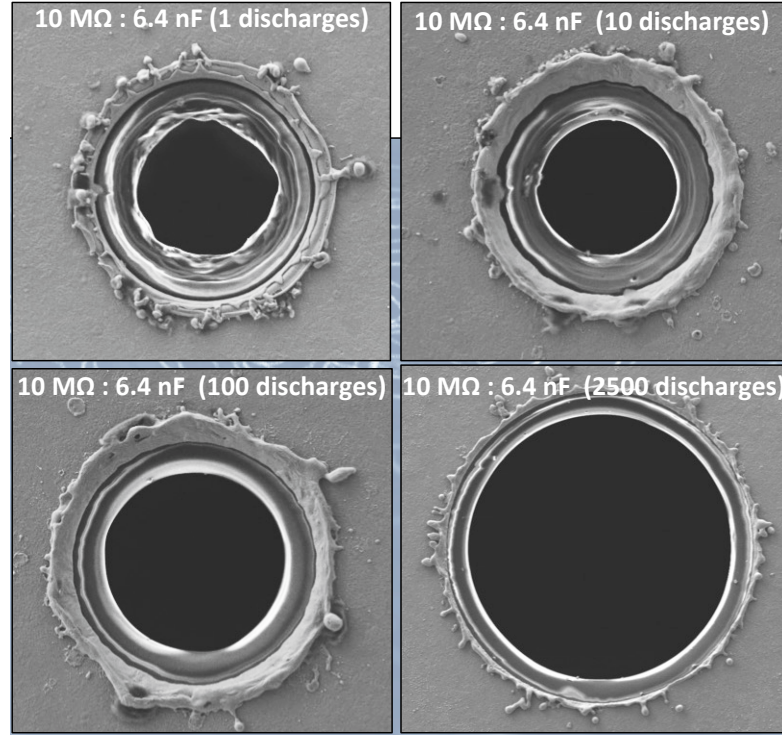


Figure 3.9: Microscopic pictures of a single hole GEM foil after a different amount of discharges [45].

thus quenches the propagation. However the voltage drop is also induced by the current that feeds the GEM electrodes during the normal operations, therefore it can lower the rate capability of the detector. A good value of the GEM bottom resistor is $\sim 100 \text{ k}\Omega$, that also rules out the influence of the cable capacitance on the propagation probability.

CHAPTER 4

Triple GEM Operational Experience

In this chapter are detailed the operations and the studies on Triple-GEM detectors for the GE1/1 upgrade of the muon system. In the first part is described the problem we were facing during the operations of the Slice Test (see Sec. 1.4.1) and the method used to find its origin. In the second part are described the studies that allowed us to implement a valuable correction to the original detector design.

4.1 Triple-GEM detectors with VFAT 2 electronics

The VFAT is a front-end Application Specific Integrated Circuit (ASIC) initially designed for the TOTEM experiment. It includes 128 analog input channels and it is designed to fulfill both triggering and tracking performance. The VFAT2 is the second version of this ASIC and it was installed both on the Triple-GEM of the TOTEM T2 telescope and on the Triple-GEM installed for the Slice Test.

4.1.1 The Slice Test

CMS approved in June 2013 the installation of a limited number of GE11 superchambers (see Sec. 1.5) into the muon endcaps [46]. Five superchambers were installed in YE1/1 during the Year-End Technical Stop YETS 2016-2017. One of them was powered with a multichannel power supply, while the four remaining were instrumented by mean of ceramic voltage divider. The motivations for this early installation are either gathering operational experience and demonstrating that the system is well integrated into the CMS online system [47].

Fig. 4.1 shows the positioning of the five superchambers installed in CMS. The four superchambers installed in the *Slot 1* were powered with a ceramic voltage divider and instrumented with the VFAT2 electronics chain [48] [49]. The superchamber installed on the *Slot 2* was powered with a multichannel power supply and, starting from January 2018, with the VFAT3 electronics [50].

The VFAT3 electronics will be used for the entire GE1/1 station therefore the analysis of its behavior in the slice test was fundamental to ensure that the detectors operate as expected. In parallel, the Prompt Feedback Analysis Prompt Feedback Analysis (PFA) group was analyzing the data coming from the local and global runs in order to verify the detector performances. Among the many others performed studies, one was focused on the identification of dead channels, whose results are detailed on Sec. 4.1.2. The slice test was concluded on December 2018 and it has been proved to be an invaluable source for gaining experience on the acquisition and analysis of the data coming from global runs, and to evaluate the real performance of the detectors. It has also given a direct feedback on the behavior expected for the final superchambers, which will be installed in 2019-2020 in the entire GE1/1 station.

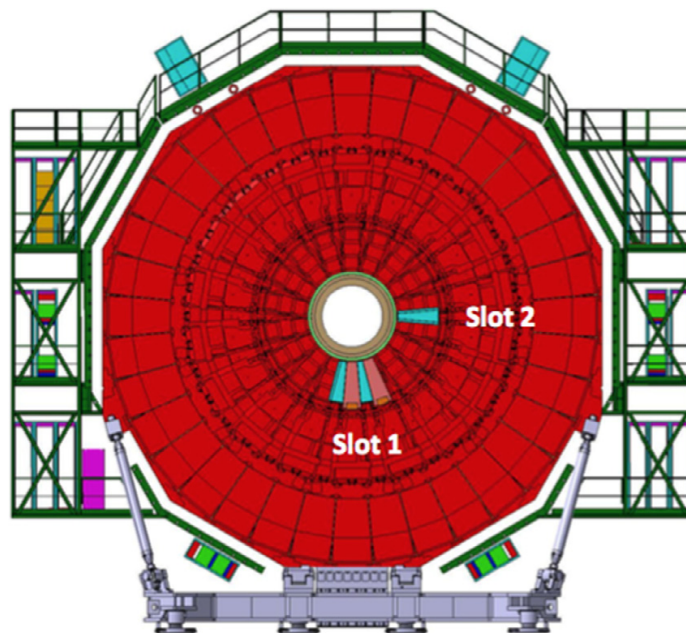


Figure 4.1: Positioning of the 5 superchambers installed for the slice test.

4.1.2 Channel Loss Data

Over the operational lifetime of the Slice Test, a fraction of the readout channel has been lost on the four superchambers instrumented with the VFAT2 electronics [51], while no channels were lost on the VFAT3 superchambers. Although the GE1/1 project foresees the installation of VFAT3 electronics, the channel loss observed for VFAT2 still threatens the proper functioning of the GE1/1 project. A loss in the number of readout channels would cause a drop in the detection efficiency and may limit the capability of GE1/1 detectors to fulfill the CMS requirements (see Sec 1.4).

As will be explained in Sec. 4.2.1, the lost channels were recognised thanks to the front-end routine referred as s-curve. The channel loss data collected over the slice test operational period are summarized in Fig. 4.2. Each point on the plot comes from the results of the s-curves performed over the 192 VFAT2 instrumented on the 4 *superchambers* installed. It can be noticed that the VFATs installed on the two layer of the same superchamber do not show the same channel lost trend over time.

The GEM management group decided to deeply study the channel loss problem by starting a new campaign called *GEM Sustained Operations*, which is detailed on Sec. 4.3. The mitigation strategies looked for, had to be found before the GE1/1 installation foreseen during the LS2 and could not upset the balance found for detectors after years of tests and measurements. As a starting point a previous

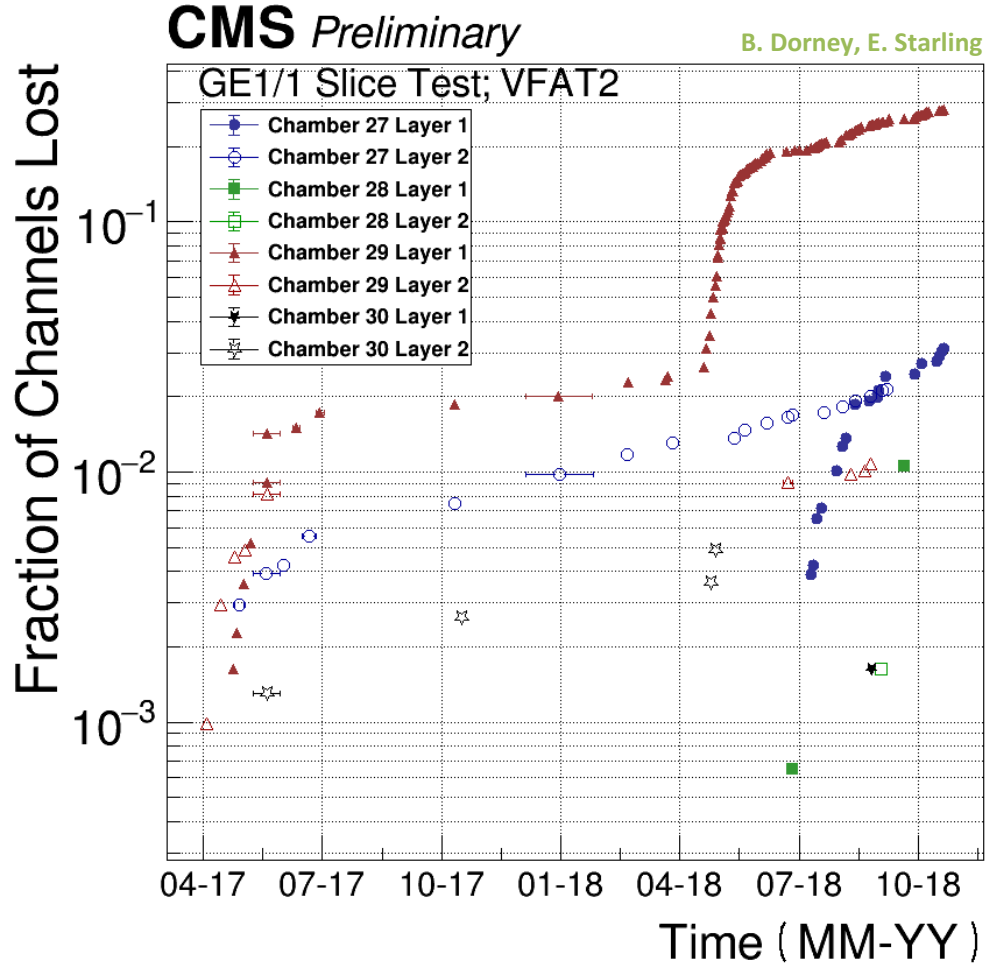


Figure 4.2: Channel loss over time for the VFAT2 instrumented superchamber during the slice test [52].

VFAT2 installation was considered.

4.1.3 VFAT2 on the TOTEM Triple-GEM

The TOTEM experiment (see Sec. 2.3.1) already installed VFAT2 technology as a front-end readout electronics for GEMs. The VFAT2 chip instrumented on those chambers didn't show anything similar to the severe damages detailed on Sec. 4.1.2 in many years of operation. The most sensible differences between TOTEM and CMS GEMs are here stressed out, in order to shed light on the channel loss root:

1. In TOTEM the gap configuration is: 3/2/2/2, in CMS 3/1/2/1;
2. $E_{\text{ind}} = 4.1 \text{ kV/cm}$ (CMS), $E_{\text{ind}} = 3.4 \text{ kV/cm}$ (TOTEM);
3. The CMS GEM foil has a surface of $\sim 4000 \text{ cm}^2$. The TOTEM GEM foil is semi-circular with 192° of angular coverage and an overall surface of 316 cm^2 ;
4. The rate of particles that reach the T2 telescope [53] is *lower* with respect to CMS GEM [54], both for positional and operational reasons.

Starting from these differences, some physical observation can be extracted. The induction gap can be modeled as a parallel plate capacitor, therefore the available energy during a discharge, is the one stored in the electric field between the two plates: $E = \frac{1}{2}CV^2$. By approximating the readout board as a flat electrode and using d , A , V respectively for the distance, the area and the voltage applied to the plates in the GE1/1 configuration, a numerical comparison can be carried out. As a first simpler approach, we can assume that the surface of a CMS GEM foil is 10 times bigger than the TOTEM GEM foil. The ratio between the available energy in the capacitor model results to be:

$$\frac{E_{\text{CMS}}}{E_{\text{TOTEM}}} \simeq \frac{A/d \times V^2}{(A/20d) \times (V \times 2/3)^2} = 45 \quad (4.1)$$

in which the numeric factors come from a taller induction gap, an higher induction field and a smaller plate surface for TOTEM with respect to CMS GEMs. So the available energy for a discharge during the slice test was $\simeq 45$ times bigger compared to TOTEM T2 telescope. If we also consider the higher rate of particles, we can conclude that, on the discharge point of view, the operating conditions for CMS GEMs are potentially more dangerous with respect to TOTEM GEMs.

4.2 Triple-GEM detectors with VFAT 3 electronics

The design of the VFAT3 is similar to the VFAT2, they can both provide triggering and tracking information. The VFAT3 however, was designed specifically to read the Triple-GEM detectors for the CMS muon upgrade. The VFAT3

has a 2 channels fast-OR for the trigger with respect to the 16 channels in the VFAT2 version. Furthermore in order to match the time resolution of the GE1/1 Triple-GEM detectors (~ 7 ns), the shaping time of the VFAT3, unlike VFAT2, is programmable, in order to reduce the ballistic deficit.

4.2.1 The Front-End Electronics: VFAT3

The Data Acquisition (DAQ) system of a GE1/1 detector, is divided in two main group: the *On-Detector* and the *Off-Detector*. The On-Detector includes:

- the front-end ASIC (VFAT3);
- the GEM Electronics Board (GEB);
- the OptoHybrid (OH);

while the details on the Off-Detector electronics can be found in [20]. The VFAT3 ASIC is mounted on a hybrid that allows the physical connection both to the 128 read-out strips and to the GEM Electronics Board (GEB). The GEB is a multilayer PCB which hosts the connection needed for the control the powering and the readout of the VFAT3. The OptoHybrid (OH) is also connected to the GEB and manages the incoming and outgoing communication with the Off-Detector electronics. The OH has also a dedicated unidirectional optical path that is used to send the data provided by the VFAT3 fixed latency trigger to the CSC system. Fig. 4.3 shows a sketch that summarizes the DAQ chain.

The VFAT3 architecture is an improved version of the VFAT2, already installed in the TOTEM forward telescope T2. Fig. 4.4b shows the block diagram of one of the 128 readout channel of the AISC. The first stage is a charge pre-amplifier, followed by a shaper and a Constant Fraction Discriminator (CFD) which concludes the analog chain. After this point the data splits in two path: the first has a fixed latency and it is used for the triggering (upper output of the Sync in Fig. 4.4b), while the second has a variable latency and it is used for the tracking (bottom output of the Sync).

Fig. 4.4a shows the channel protection placed inside the ASIC. It consists of an 8Ω resistor followed by an ElectroStatic Diode (ESD) diode and it is designed to provide robustness to the high current flow induced by a discharge.

The VFAT3 provides two main output paths: the variable and fixed latency one. The former is used for full granularity data transmission while the latter provides fast trigger data that can be put in coincidence with the CSC data, in order to produce a reliable muon trigger. Thanks to the programmable shaping time, the induced charge can be fully integrate, improving the Signal to Noise Ratio (SNR) and avoiding the ballistic deficit. The simulations assess the time resolution of the VFAT3 to be $\sim 5\ \mu s$, even at the maximum programmable shaping time. The

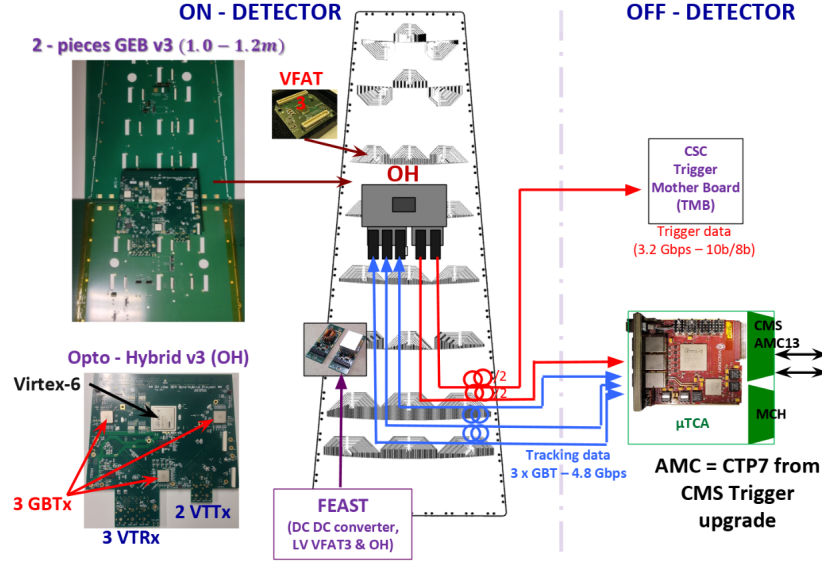
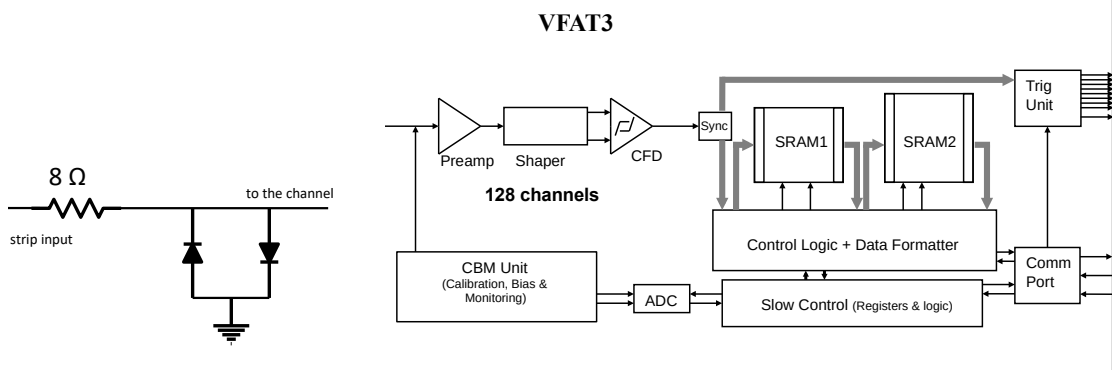


Figure 4.3: Summary of the On-Detector and Off-Detector electronics. The 24 VFAT3 communicate with the OH by mean of the paths provided by the GEB. The communication with the Off-Detector electronics is handled by the OH.



(a) VFAT3 channel input protection.

(b) The VFAT 3 diagram block [55].

measurement of the Equivalent Noise Charge (ENC) is possible by mean of the VFAT3 calibration circuit, which is able to deliver internal pulses to each channel individually [55]. The pulses can be sent in two different modes:

Voltage step pulse in which a voltage step pulse is applied to a series capacitor, generating a δ -like pulse at the preamplifier input, with programmable polarity, amplitude and timing.

Current pulse in which a a current pulse is applied at the preamplifier input, programmable in current magnitude and pulse duration.

In the voltage step pulse mode a 100 fF capacitor is charged at a voltage provided by an 8-bit current Digital to Analog Converter (DAC), in such a way that the increase of 1 DAC unit increases the injected charge by $Q = CV \simeq 0.1$ fC (each VFAT is calibrated on bench to exactly measure the conversion parameters). Further details regarding the calibration module and on the VFAT architecture are reported in [50]. Regardless of the selected pulse mode only one channel at a time is injected, in order to have an higher accuracy on the injected charge.

Equivalent Noise Charge (ENC)

The ENC is the charge to be induced on the readout strips in order to build, on the front-end electronics, a signal that has a Signal to Noise Ratio (SNR)= 1. In other terms, for GEM detectors, the ENC is the equivalent charge that would be read by the front-end electronics due to noise. It is a crucial parameter for both triggering and tracking, because it is closely related to the efficiency. Any avalanche that induces a charge $Q \leq ENC$ on the strips, can not be discriminated from the noise. A detailed discussion of noise in the readout electronics for high-energy physics is beyond the goals of this thesis. Here a simple and realistic example shows how the detector capacitance contribute to the ENC.

ENC vs strip capacitance

The first block in the readout electronics chain is a charge preamplifier. This first amplification stage is the one that contributes the most to the noise. An equivalent circuit is shown in Fig. 4.4. Throughout the text we will assume op-amps to be always ideal (input impedance = ∞), then the output voltage, in the Laplace domain, results to be:

$$V_{\text{out}}(s) = \frac{R}{1 + s RC} \times I_{\text{det}}(s) \quad (4.2)$$

Let us simply assume that the avalanche induces a step pulse current on the readout strip, with amplitude I_0 and time-width T . For $t \in [0, T]$ the current step pulse in the frequency domain is $I_{\text{det}}(s) = I_0/s$. Now, by inverting the Laplace transformation, it is possible to recover the output voltage in the time

domain:

$$V_{\text{out}}(t \in [0, T]) = I_0(1 - e^{-\frac{t}{RC}})R \quad (4.3)$$

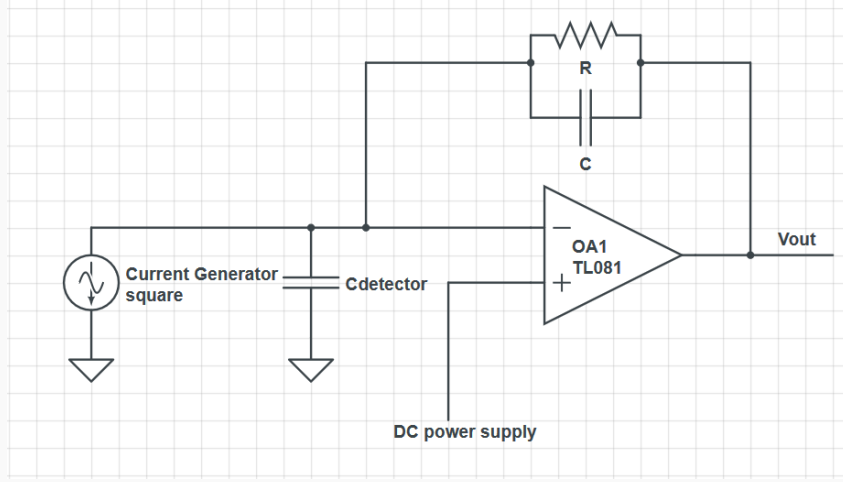


Figure 4.4: Simple equivalent input circuit for a charge-preamplifier.

The Eq. 4.3 looks identical to the one that describes the charging process of a capacitor in a circuit with time constant $\tau = RC$, when a current generator $I = I_0$ is connected. Referring again to the Eq. 4.3, if $\tau \gg T$, it is possible to neglect the discharge process through the resistor R so that all the injected charge is stored on the capacitor plates. It can be modeled as a power series expansion of the exponential function around $-\frac{t}{CR} = 0$:

$$V_{\text{out}}(T) = \frac{T \times I_0}{C} = \frac{Q}{C} \quad (4.4)$$

The Eq. 4.4 states that the charge-preamplifier integrates the detector output current when the condition $\tau \gg T$ is matched, returning an output voltage proportional to the total injected charge. From Eq. 4.4 one can also notice that the charge measurement sensitivity scales with $1/C$. Fig. 4.5 shows the output voltage for a step pulse current input signal when $\tau = 10 \times T$.

Now let us consider, for the sake of simplicity, only the noise contribution coming from the voltage source. It can be modeled as signal source $N(s)$ connected to the non-inverting input of the operational amplifier. Finally, let us suppose that the detector High Voltage (HV) is OFF, so that no current is induced on the readout plane by avalanches. The output voltage in the Laplace domain is:

$$V_{\text{out}}(s) = \frac{1 + R(C + C_d)s}{1 + sRC} \times N(s) = \frac{1 - s/s_z}{1 - s/s_p} \times N(s) \quad (4.5)$$

where

$$\begin{cases} s_z = \frac{-1}{R(C+C_d)} \\ s_p = \frac{-1}{RC} \end{cases}$$

where $s_z \leq s_p$ represent the zero and the pole frequencies of the transfer function. While the pole frequency does not depend on the strip capacitance C_d , the zero pole moves down as C_d increases so that the noise bandwidth scales linearly with C_d . At the transfer function plateau, the noise gain is:

$$V_{\text{out}}(s = \infty) = \left(1 + \frac{C_d}{C}\right) \times N(s = \infty) \quad (4.6)$$

so also the gain increases linearly with C_d . Typical C_d values for GE1/1 detectors lie within [9 pF, 88 pF]. Generally, if the preamplifier has Z_d and Z as the input and the feedback impedance respectively, the transfer function for the noise is $1 + Z/Z_d$, therefore decreasing the input impedance increases the ENC (see Fig. 4.6).

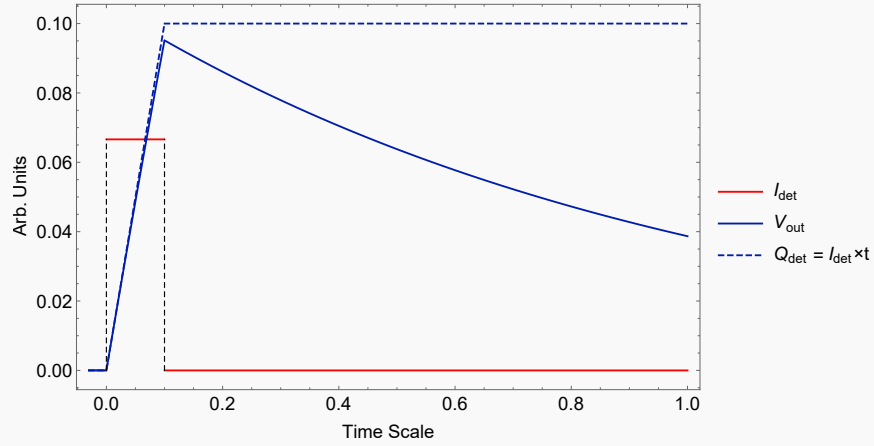


Figure 4.5: Charge-preamplifier output signal for step pulse current input, when $\tau = 10 \times T$. In dashed blue the total injected charge, the ballistic deficit is barely noticeable.

This simple model shows how does the detector strip capacitance impact on the signal noise. The situation for a real detector is much more complex, as it either involves many other physics processes, here neglected, and for the amount of details that have been discarded in the previous evaluation. However this simple evaluation shows that **the *intrinsic* noise of the front-end electronics is proportional to the load capacitance even when there is no signal coming from the detector itself.**

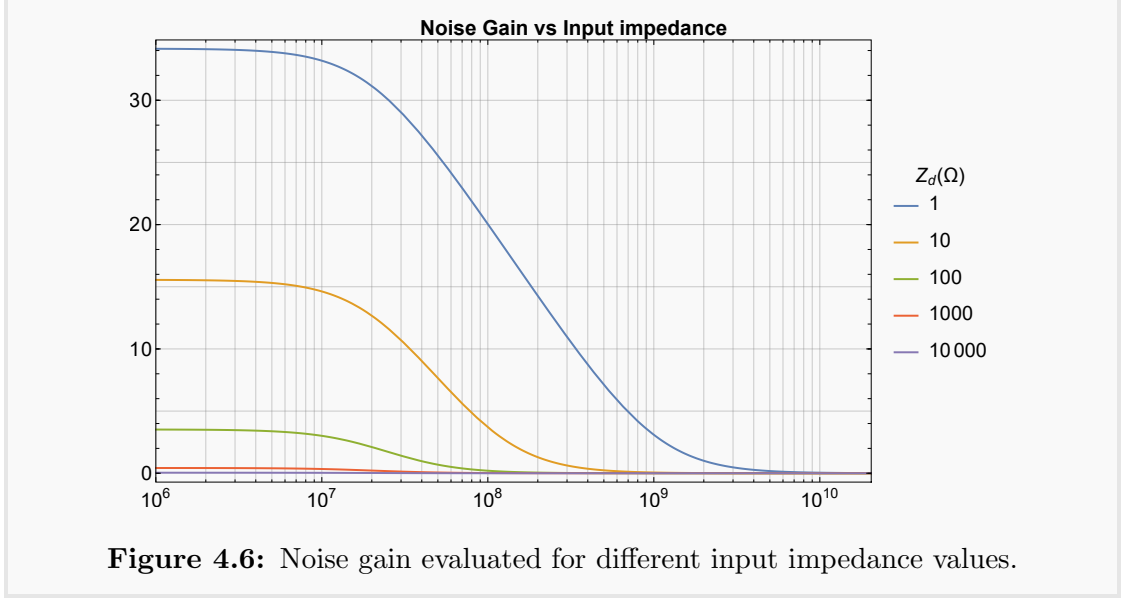


Figure 4.6: Noise gain evaluated for different input impedance values.

4.2.2 Front-end calibration routines

The VFAT3 calibration circuit can be programmed through the back-end electronics. Therefore a set of routines has been written in order to allow a user-friendly interaction with the front-end chip. In particular, the routine called s-curve allows the monitoring and the calibration of the readout channels. It consists of sending N pulses, either in current or voltage step mode, to the channel input at a fixed discriminator threshold Q_{thr} . The number of events that overcome the discriminator threshold is stored, then, when all the N pulses have been sent, the amplitude of the pulses is increased by 1 DAC. The scan ends when the pulse amplitude has been shifted along the whole 8-bit DAC range. Similar algorithms, based on the pulses of the calibration module, can be used to calibrate the channel readout chain (e.g. thresholds, timing) and to measure its intrinsic electronics noise.

The s-curve algorithm has been implemented in a modular way, so it can scan a whole VFAT (128 channels) or even an entire GE1/1 detector ($128 \times 24 = 3072$ channels). In the ideal scenario, after N calibration pulses, the discriminator output is an Heaviside function centered on the DAC that corresponds to the discriminator threshold Q_{thr} . However due to the noise the discriminator output assumes an *s shape*, which is the reason of the name. If we consider the contribution of the noise, after multiple pulses at a fixed DAC value, it is reasonable that:

- for $Q(\text{DAC}) \ll Q_{\text{thr}}$ almost no pulses will trigger the discriminator;
- for $Q(\text{DAC}) \simeq Q_{\text{thr}}$ a fraction of the pulses will trigger the discriminator, depending on the aleatory amplitude of the noise when the pulse is injected;
- for $Q(\text{DAC}) \gg Q_{\text{thr}}$ almost all the pulses will produce an output.

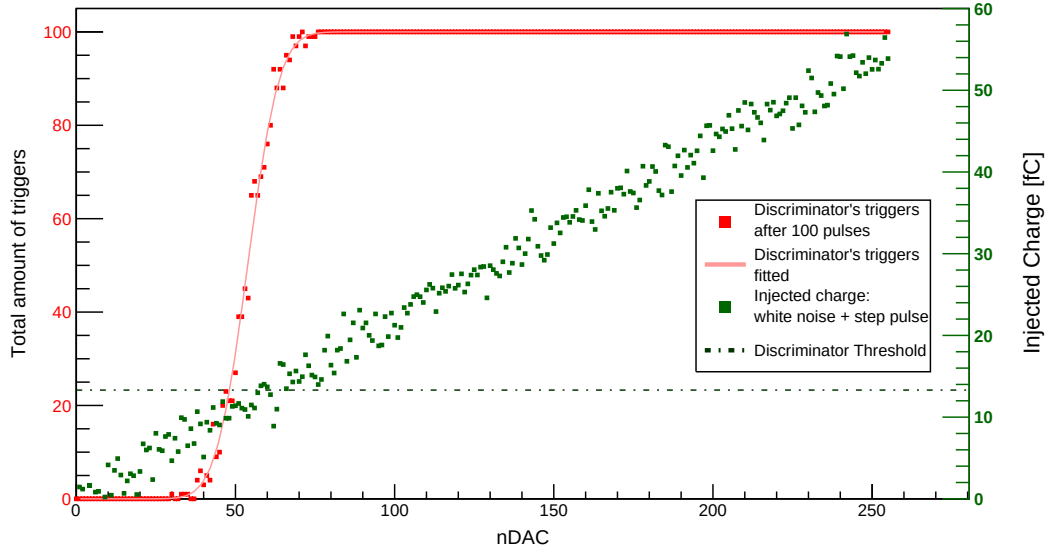


Figure 4.7: The discriminator output to a gaussian white noise added to the ideal pulse amplitude; 100 pulses have been generated for each DAC value. Red points represent the number of discriminator triggers, in light red the fit. The green points represent one of the 100 pulses simulated. The threshold is set to 54 DAC unit, i.e. 12.7 fC.

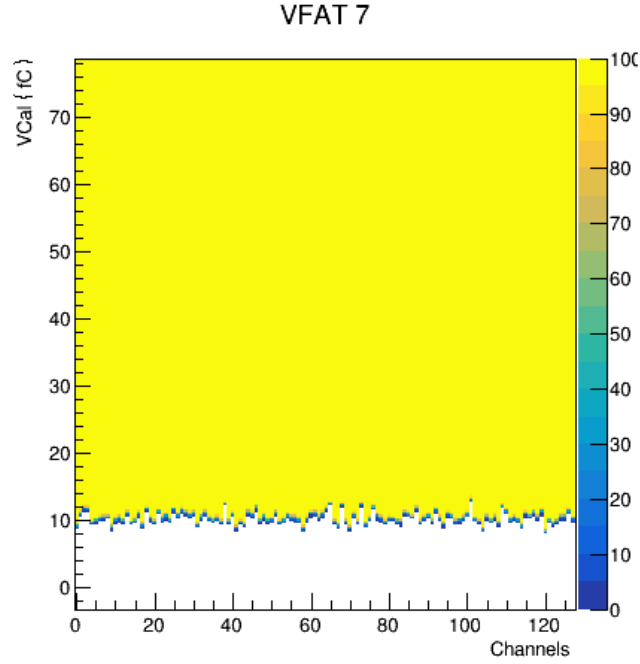
A simulated example is shown in Fig. 4.7. The noise is modeled as a Gaussian white noise process with $(\mu = 0, \sigma = 8)$ and is added to the ideal injected amplitude. For each DAC value, 100 pulses have been simulated and compared with the threshold. Finally, the number of passing events, has been fitted with the Cumulative Distribution Function (CDF) of a gaussian distribution, usually called error function $erf(\mu, \sigma)$. The fit results are shown in Tab. 4.1. This evaluation shows that the (μ, σ) fit parameters are good estimators for the CFD threshold and for the ENC.

The CFD threshold of each VFAT channel is set by mean of a DAC register. The conversion of the CFD threshold from DAC to charge is possible by taking several s-curves at increasing value of the CFD threshold and fitting each one to obtain a set of (μ, σ) pairs. Then, by linear fitting the μ s and the correspondent CFD threshold expressed in DAC unit a conversion can be established. The average σ s and μ s of the VFAT as a function of the CFD threshold expressed in DAC, are shown in Fig. 4.10b.

In order to summarize the s-curve data collected from the 128 channels of a single VFAT, a 3D plot has been adopted (see Fig. 4.8). The x-axis shows the channel number, the y-axis the injected charge with the calibration pulse, where the conversion between the DAC unit of the calibration module and the charge injected, is obtained by mean the conversion parameters provided by the electronics

Table 4.1: Superposition of the calibration pulse with white noise: fit results

Parameter	Value	Error
χ^2/N	1.97	
μ	53.84 DAC	0.075
σ	7.80 DAC	0.11

**Figure 4.8:** Zero input capacitance s-curves results for the 128 channels of VFAT7. Peaking time = 75 ns, medium gain, vt1 = 100 DAC units.

team. Finally on the z-axis is shown the number of passing events. At a glance it is possible to compare the response of different channels and ensure the good functioning of the whole front-end.

4.3 GEM Sustained Operations

A new R&D campaign was started in June 2018, named *GEM sustained operations*. The set goals were:

- Understand the origin of VFAT2 channel loss observed in the *Slice Test*;
- Investigate if channel loss would occur when using VFAT3;

- Identify the channel loss mechanism(s) and find the possible mitigation strategies.

The program of operations included the monitoring of the front-end electronics of the *Slice test* and a series of measurements to be performed in the 904 laboratory, aimed to investigate the source of the channel loss. Since the final version of the ASIC for the GE1/1 detectors is the VFAT3, it has been decided to perform all the laboratory measurements on the VFAT3, with the idea of validating the ultimate front-end electronics.

The channel loss on VFAT front-end electronics has been never observed before, so there were no recommendations given from the past studies. Therefore all the hypothesis on the channel loss origin has to be carefully tested. To begin with it was necessary to ensure that under normal operating conditions there is no channel loss at all. It was also necessary to ascertain that no damages are caused by having electron avalanches while the electronics is accidentally turned off. The test that includes these hypothesis was named *Non-destructive test* and foresaw three different operational modes: *Normal Operation*, *Improper Operation* and *Irradiation*, which are detailed on Sec. 4.3.1.

Lastly another reasonable source for the channel loss is the large amount of current on the channel input as a result of a discharge. In order to test the discharge hypothesis, the GE1/1 detector needed to be operated at extreme gain values, largely outside the design conditions, and irradiated with HIPs. The combination of these two factors allowed the triggering of controlled and localized discharges. This test has been named *Potentially destructive test* and it is detailed further on in this thesis (see Sec. 4.3.2).

The readout plane of GE1/1 detectors is sectorized in 24 independent portions of 128 strips each. Therefore up to 24 simultaneous front-end tests could be tested with a single detector. However, due to the different working gains, the two tests mentioned before strictly needed different setups.

4.3.1 Non destructive test: method and results

The detector assigned to the non destructive test was a 10th generation GE1/1 detector built at CERN, named GE11-X-S-CERN-0011. Fig. 4.9 shows the detector instrumented with the GEB.

The characterization and calibration of the readout electronics were carried out as a first step. Testing the front-end electronics without detector allowed us to:

- ensure that the electronics work properly avoiding any possible bias due to the detector;
- measure the ENC without the load capacitance due to the detector.

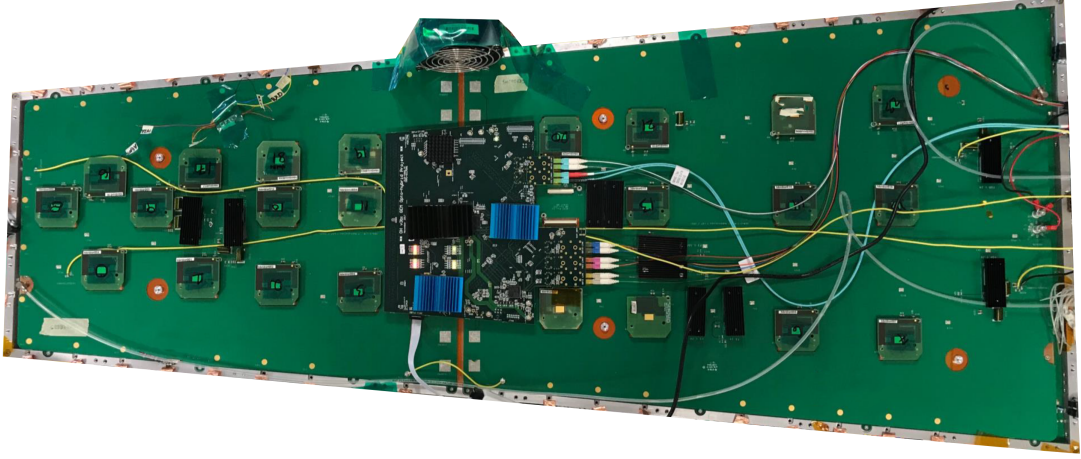


Figure 4.9: Non destructive setup instrumented with the electronics and without the cooling plate. The electronics is cooled down by a small fan.

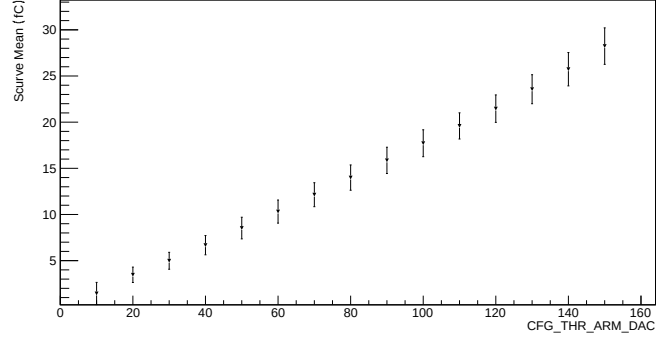
The ENC for 24 *VFAT3a prot* (14 properly working) instrumented on *GEB3b* with OH(v3c), resulted to be 0.236 fC equivalent to $\simeq 1473$ electrons as expected from the design [48], and it was independent from the discriminator threshold. The same measurement was performed with the electronics instrumented on the detector, while the HV was kept off, resulting in $1.123 \text{ fC} \simeq 7018 e^-$ of ENC. Finally, in order to evaluate the contribution of the HV to the ENC, the measurement was performed again with the HV on. The results are summarized in Fig. 4.10.

Fig. 4.11 highlights a comparison between the three configurations in a *box and whisker plot*: it shows, for each VFAT position, the ENC lowest value, the interquartile, the median, the upperquartile, the higher value and the average. It is important to notice that the noise difference between the two HV status is not significant. Due to the fact that the readout partitioning area increases when $i\eta$ decreases, the strip capacitance increases as well, which is visible from VFAT position 0 to 7; 8 to 15; and 16 to 23. Furthermore, for all the connected positions the ENC of the not connected configuration is clearly distinguished from the ENC *On-Detector*, so it is possible to determine a threshold ENC to discriminate between *connected/disconnected* channel. This is a crucial parameter to help with channel burned/detached discrimination; this technique has been largely used both in the evaluation of the *Slice test* channel loss, and in the damage probability measurements detailed later on.

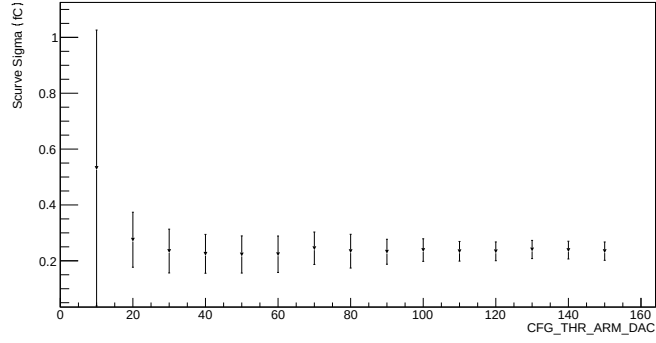
Once the ENC characterization, the DAC and ADC calibrations of the front-end were done, the detector was instrumented with the electronics for the non destructive test. Three operational regions were defined, as shown in Fig 4.12:

Normal operations : operated as designed for GE1/1, cosmic rays irradiated;

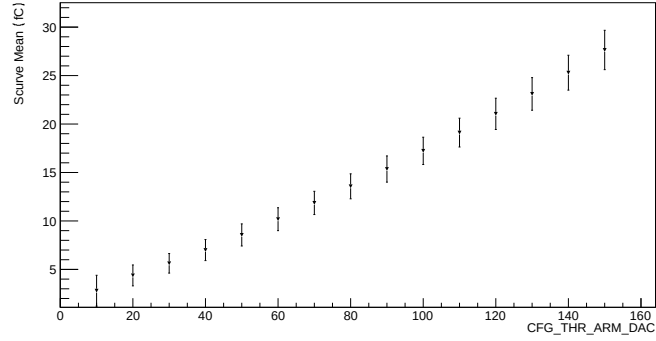
^{109}Cd irradiated operated with an additional radiation source;



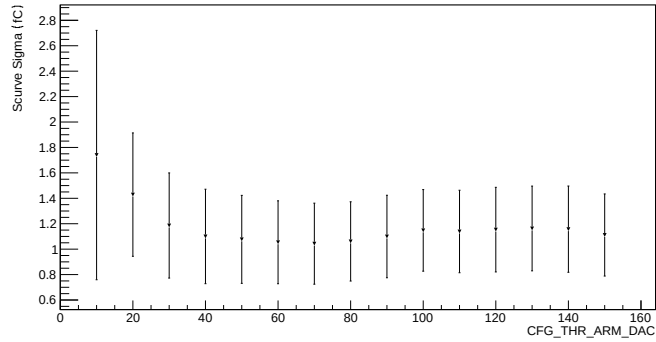
(a) Off-Detector: Average VFATs μ fit parameter vs discriminator threshold



(b) Off-Detector: Average VFATs σ fit parameter vs discriminator threshold



(c) On-Detector: Average VFATs μ fit parameter vs discriminator threshold



(d) On-Detector: Average VFATs σ fit parameter vs discriminator threshold

Figure 4.10: Summary of the fit parameters for s-curve taken with threshold DAC in the range $[10, 150]$. The data on the two plots on top are collected with the VFATs not connected to the detector readout. They were instead connected in the two plots on bottom.

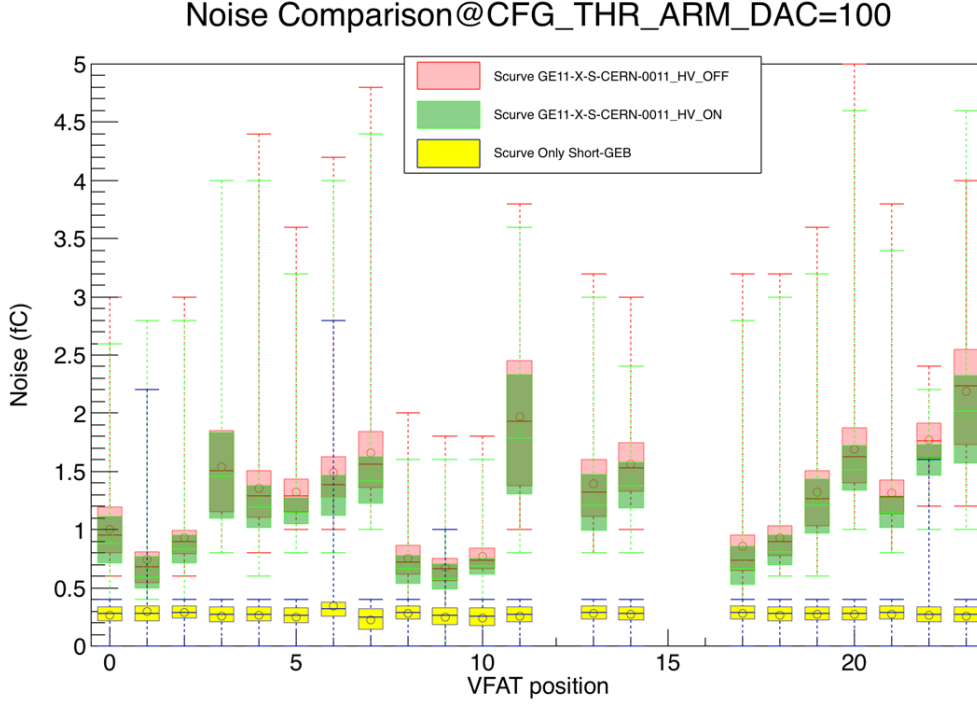


Figure 4.11: ENC comparison for each VFAT position in 3 configurations: bare electronics (yellow), detector with HV off (pink), detector with HV on (green) [56].

Improper operations operated with the low voltage OFF while the detector was ON.

The voltage differences and the electric fields at which each gap was powered, are detailed on Tab. 4.2. Based on former measurements of the detector gain for the quality control (QC5 detailed in [57]), that voltages corresponded to $G_{\text{eff}} = 10^4$.

Table 4.2: The voltage differences and the electric fields in each gap of the GE11-CERN-X-S-0011 detector while performing the *Non destructive test*.

	Drift	GEM1	Tran1	GEM2	Tran2	GEM3	Ind
ΔV (V)	756	378	294	370	588	353	420
E (kV/cm)	2.53	75.6	2.94	74.1	2.94	70.6	4.2

An s-curve was performed every day over all the 128 channels of each instrumented VFAT, in order to monitor the channel condition. The results are summarized in the following 3 rows $\times$ 8 columns 3D plots called *Time Plot Series*. On the x-axis is shown the s-curve date (day), on the y-axis the channel number while on the z-axis the ENC of the channel. The 3 rows $\times$ 8 column plot reflects

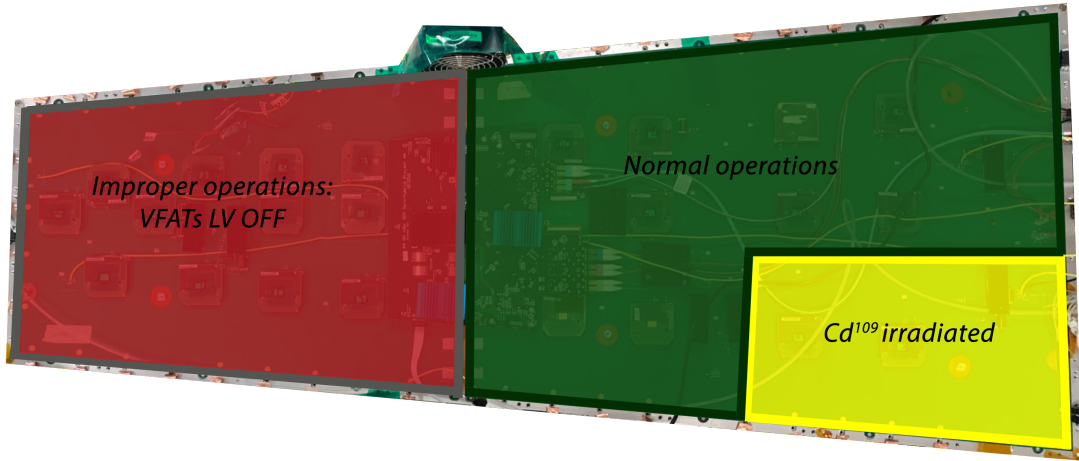


Figure 4.12: Schematic of the set up instrumented for the non destructive test. In red the improper operations region, in green the normal operation one and in yellow the ^{109}Cd irradiated zone.

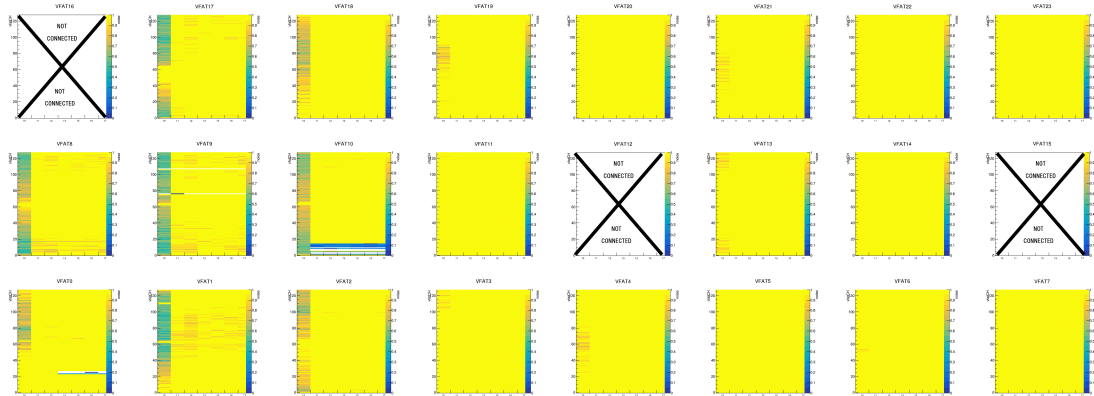
the actual disposition of the VFATs on the detector, and should not be confused with the VFAT s-curve plot shown before.

Any relevant change in the noise of one of the 3072 total channels will pop up with a change of color. Due to connectivity problems, 3 VFAT positions out of 24 were non-functional at the beginning of the test, therefore are not shown in the first plots. However for 2 of them the connection was recovered later on, and they reappear in subsequent plots. The *Time Plot Series* for three months of non-destructive tests are shown in Figs. 4.13 and 4.14. The script that builds up these plots, makes use of the fitting parameter of the daily s-curves. Therefore an empty entry on the final plot, may indicate either a *non responding* channel or a *failed fit*.

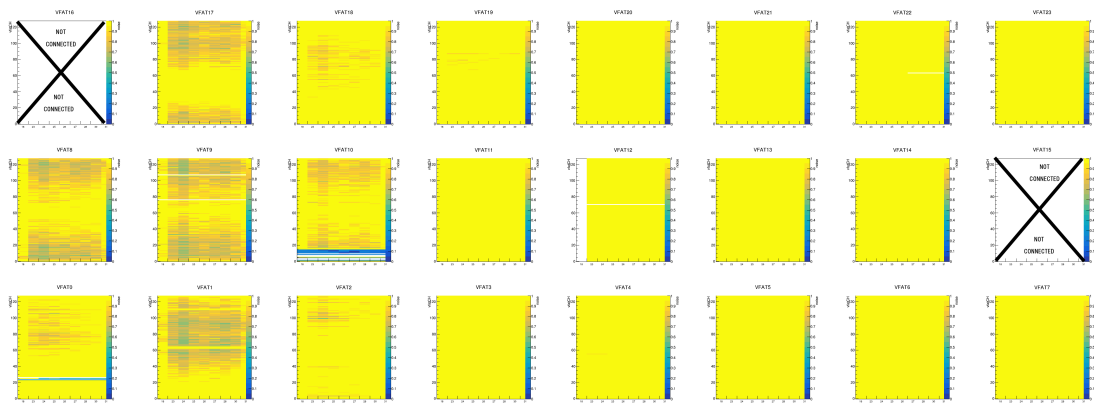
On July 11 at 14.29 an over-current event shut down the detector because the current overcame the $2\mu\text{A}$ limit set on the HV power supply. From that moment on, the VFAT 10 showed few channels with *low noise/blank* s-curves. For these low noise channels, it is possible to hypothesize that the 8Ω input protection resistors (see Sec 4.2.1) broke down, disconnecting the readout electronics from the detector. Therefore without the load capacitance of the detector, the ENC results much lower. As a consequence of the over-current event on July 11, the whole detector average noise increased (see Fig. 4.15).

Another over-current event happened on July 13 at 00.01. After this event, the VFAT 0 shows *low noise/blank* s-curves.

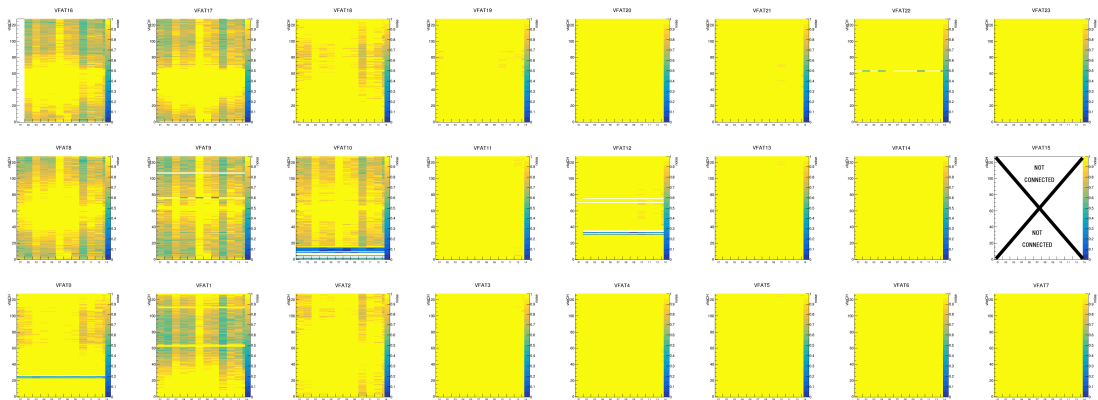
The empty entry on VFAT 22 on July 27 is due to a bad fitting, while on August 1st at 20.22 another over-current event shut down the detector, this time with a negative current drawn. The event was caused by an user mistake during the operations: while the detector was powered at $G_{\text{eff}} = 10^4$, VFAT12 was pushed on



(a) 10-17 July 2018

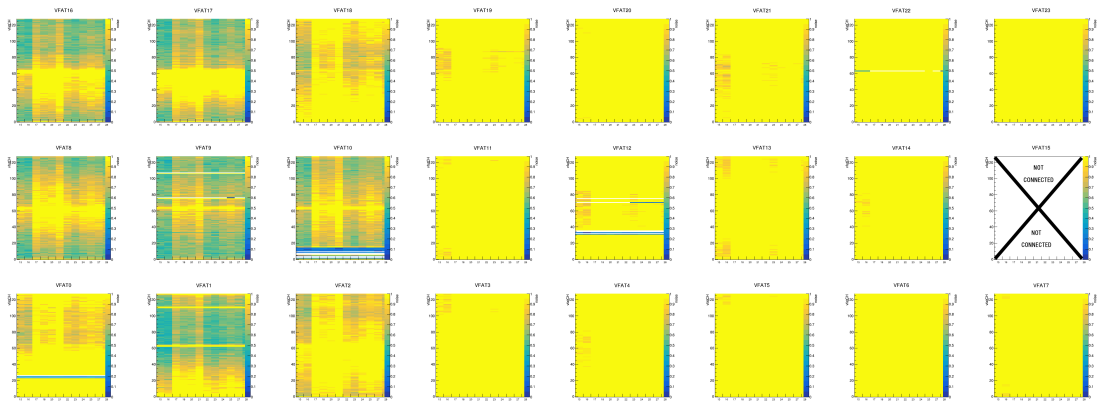


(b) 18-31 July 2018

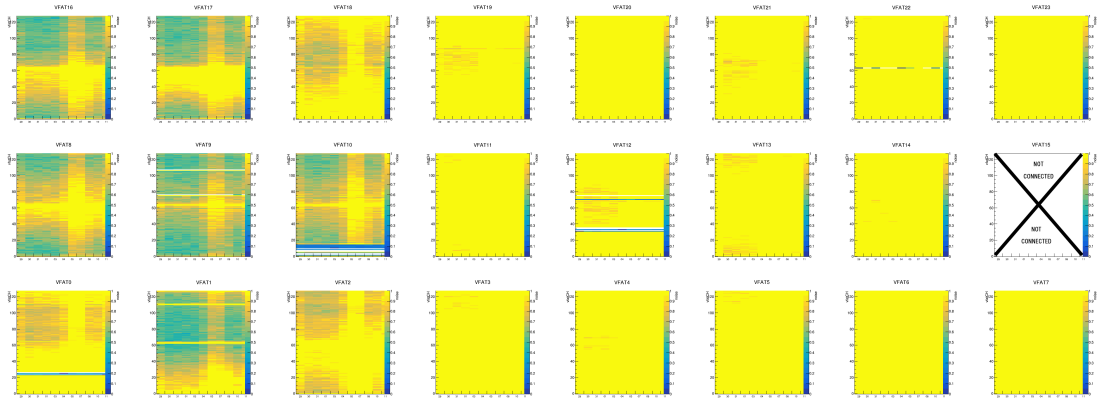


(c) 01-14 August 2018

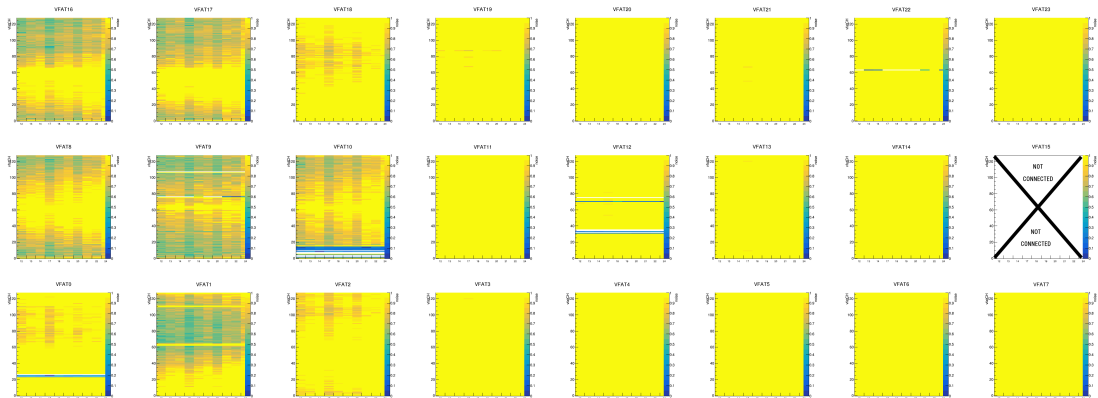
Figure 4.13: Summary of the first half of the non-destructive test. The three plots show the ENC of each channel during time, each covering a period of two weeks.



(a) 15-28 August 2018



(b) 29-11 September 2018



(c) 12-24 September 2018

Figure 4.14: Summary of the second half of the non-destructive test. The three plots show the ENC of each channel during time, each covering a period of two weeks

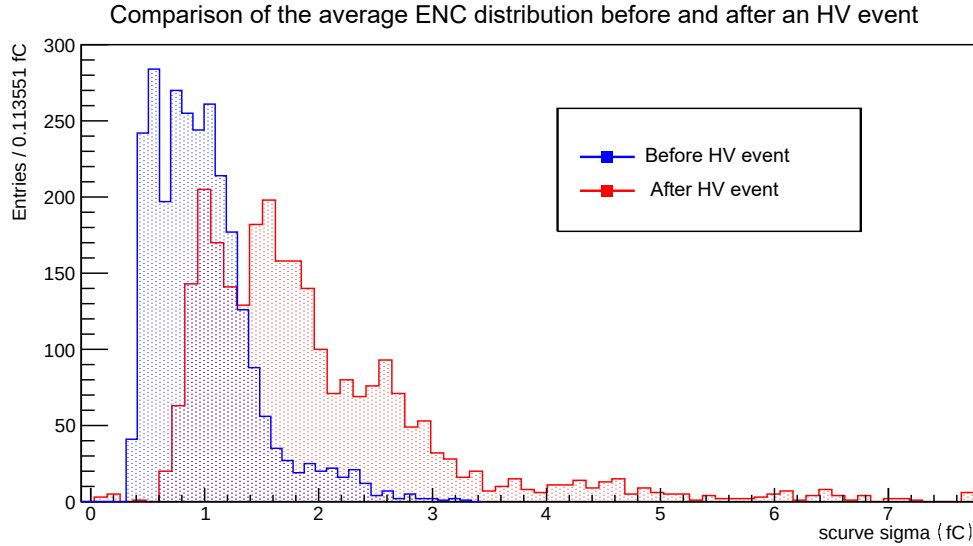


Figure 4.15: Comparison of the ENC distribution of all working VFATs before and after the HV event happened on July the 11th.

the readout plane in order to plug it in. Most probably this caused a narrowing of the induction gap, with an increased electric field and the breakdown of the gas gap, so that the discharge propagated to the front-end electronics. Even if it was an unwanted event, it suggested a correlation between propagated discharges and channel loss, shedding new light on the channel loss root.

After August 1st, were recorded no more channel lost. In particular the detector didn't show HV instability anymore. The initial instability could be ascribed to generic micrometric particles inside the chamber that have been released after the handling of the detector or due to the gas flow, and that could lead to electric field distortions or shorts inside the GEM holes. This is something we should be aware of during the GE1/1 commissioning and installation. If a similar scenario appears during the first HV power cycle of the detector after the installation, the operator has the possibility to modify the electric fields in the chamber, in order to avoid the propagation of discharges toward the anode plate while the micrometric particles are burned in GEM hole discharges. Finally the average of the ENC on all VFAT positions, fluctuated across days, probably due to environmental effects that were not under control in the laboratory.

In conclusion, the detector GE11-X-S-CERN-0011 after almost 3 months of continuous operations, showed 4 HV trip-event, 3 of which were correlated with channel loss: this was the first time that channel loss has been seen on the VFAT3 ASIC. No channel loss were related to a distinction between the three different operation regions. The data collected and the channel loss behaviour observed, corroborated the hypothesis of channel loss due to discharges that reach the anode plane and discard the other hypothesis. Therefore the *Potentially Destructive Test*

is fundamental to shed lights on the details of the phenomenon and the possible mitigation strategies.

4.3.2 Potentially destructive test

The non-destructive test showed that channel loss is related to discharges, most probably with the ones that propagate to the anode plane. However, except for the user caused discharge, it is hard to control where the discharge is triggered and make a strong correlation with the channel loss. Furthermore it is hard to mitigate the channel loss, if we are not able to reproduce it in a controlled way.

A different set-up was built in order to systematically study the effect of localized discharges on the front-end electronics. It is possible to trigger discharges by operating the detector at a very high gain and irradiating it with a source of α -particles (which are Highly Ionizing Particle (HIP)). The α -particles have an higher mass with respect to the electron ($M_\alpha \sim 10^4 m_e$) and proton ($M_\alpha 4 m_p$), and are doubly charged (He^{2+}). These properties lead to an energy loss much higher for α -particles with respect to electrons or protons. As a consequence an higher number of electron-ion pairs are freed in the gas, which is the reason why they are commonly referred as highly ionizing particles HIP (see Fig. 2.1). Another consequence of the higher energy loss is the fact that the penetration depth of α -particles is much smaller with respect to protons and electrons.

We used the ^{241}Am as a source of α -particles, which are emitted with 5.6 MeV of energy. Therefore their range in copper is $\simeq 5 \mu\text{m}$ while it is $\simeq 53 \mu\text{m}$ on paper. This means that a paper sheet is enough to stop the α_s , while a $2 \mu\text{m}$ Mylar film it is not.

In order to let α -particles interact with the gas in the chamber, the detector GE11-CERN-X-L-0002 was modified: the standard drift PCB was replaced with a different one, on which several holes were drilled, as is shown in Fig. 4.16. The holes are strictly necessary in order to let the α -particles interact with the gas. During the detector re-assembly, the holes have been closed with a thin film of Mylar ($2 \mu\text{m}$), to ensure gas tightness. Finally, after the assembly, the HV stability was ensured with the Quality Control (QC)6 test [57].

The detector was then instrumented with 10 VFAT3, the GEB and the OH. A noise characterization of the electronics was performed and the results indicated that, among the available holes, the most suitable position (e.g. lower ENC on detector) to perform the test was on the VFAT 7 position. In this position an effective gain measurement was performed, the results are shown in Fig. 4.17. The effective gain was also measured as a function of the induction and drift field, the results are shown in Fig. 4.18). The ^{241}Am was positioned on the hole drilled in the drift board in correspondence of the VFAT7 position. The α -particles rate was measured and the results are shown on Fig. 4.19. The detector showed HV

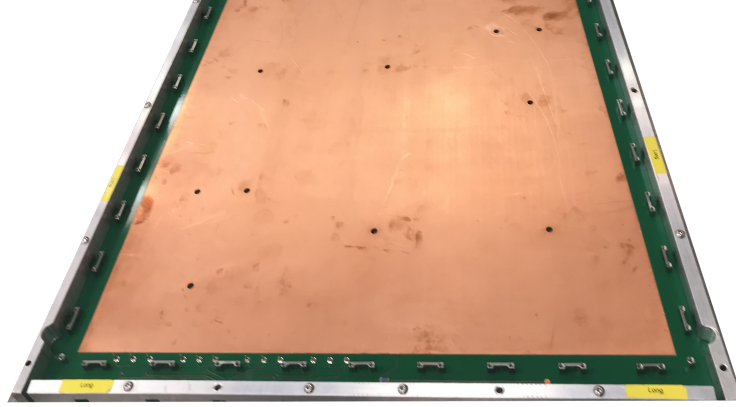


Figure 4.16: Portion of the drift PCB with drilled holes. Only few holes were used hence, after the assembling, most of them were closed with the tape to avoid gas leaks.

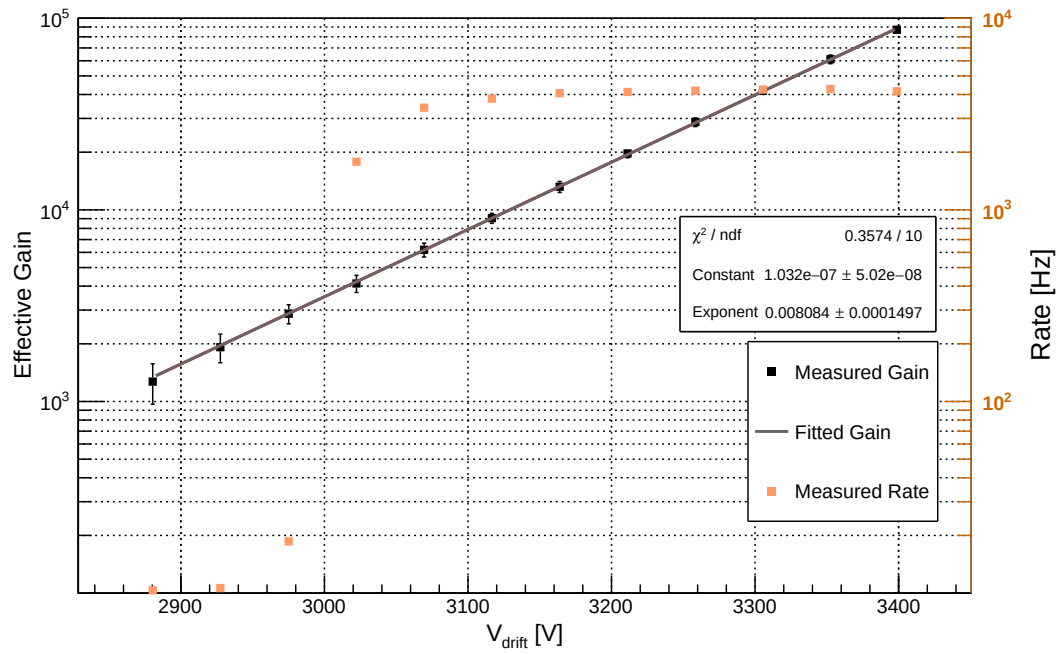
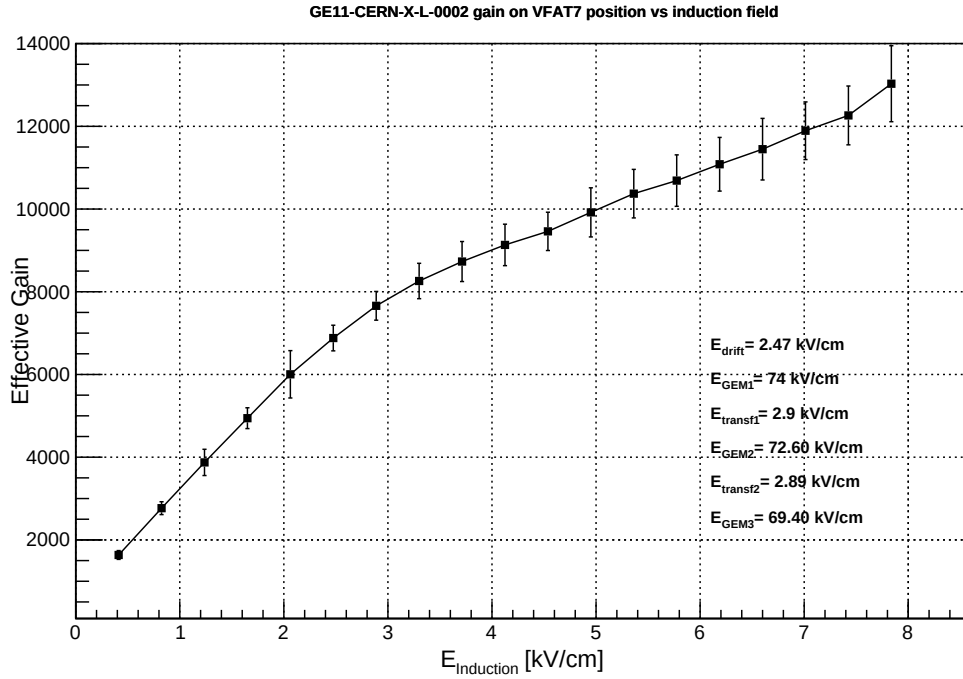
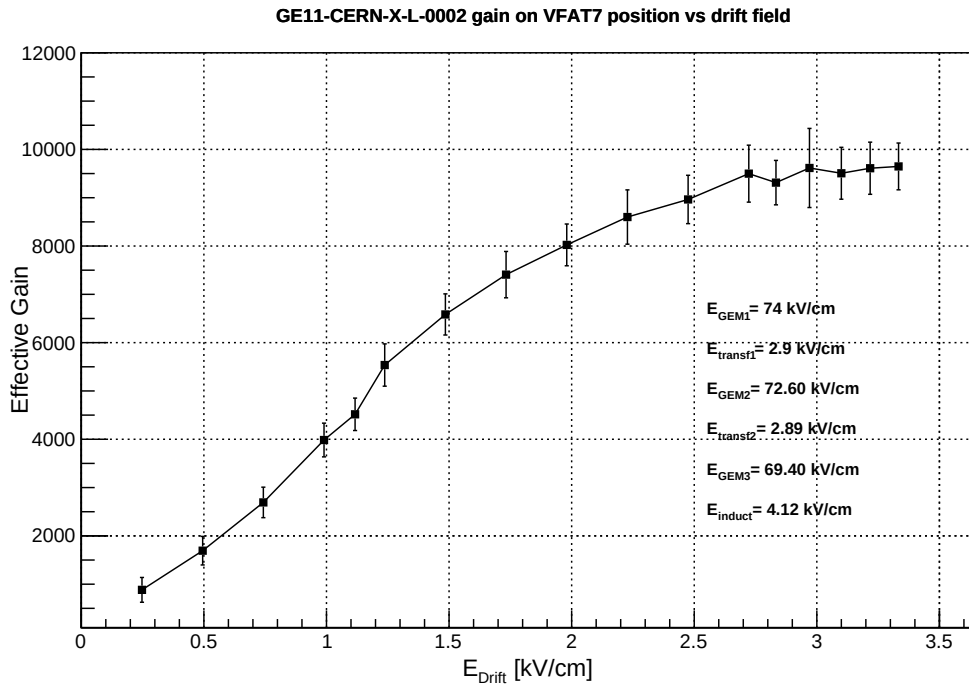


Figure 4.17: Effective gain on the VFAT 7 position as a function of the voltage on the drift electrode.



(a) Effective gain on the VFAT 7 position as a function of the electric field in the induction gap.



(b) Effective gain on the VFAT 7 position as a function of the electric field in the drift gap.

Figure 4.18: The effective gain measurement taken in the VFAT 7 position. In (a) the induction field is increased while all the other gap fields were kept at their $G_{\text{eff}} = 10^4$ value. Similarly in (b) only the drift field was increased.

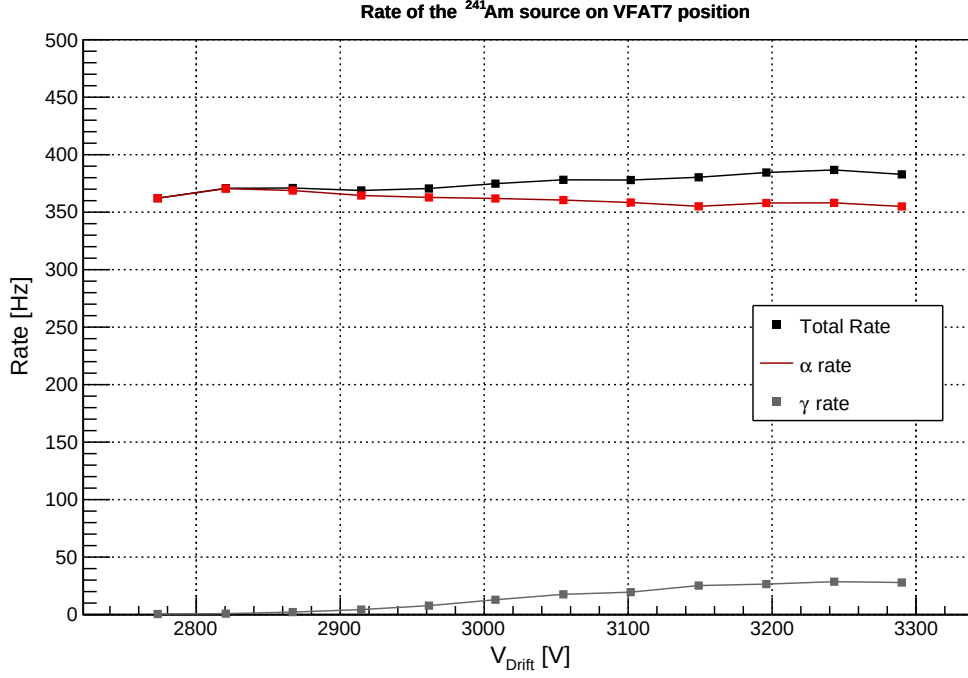


Figure 4.19: On-Detector measurement of the ^{241}Am rate.

instability: a discharge was triggered at $G_{\text{eff}} = 4 \times 10^4$, while the source was shielded with a paper sheet. As a consequence a short-circuit between the top and bottom electrode of the second GEM foil appeared. The resistance measurement performed on the second GEM foil returned $12 \text{ M}\Omega$, which corroborated the hypothesis of a single HV sector short-circuit (each HV sector in which the GEM electrode is segmented, is powered through a $10 \text{ M}\Omega$ resistor, see Sec. 1.5). In order to establish where the short-circuit was located, a scan along the $i\phi = 2$ partitions was performed with ^{109}Cd . The detector was powered at $G_{\text{eff}} = 2 \times 10^4$. On the central column ($i\phi = 2$), the overall current coming from the 8 readout partitions was sent to the Keithley 6487 pico-ammeter, while the 16 remaining readout sectors were terminated at 50Ω . The setup is shown in Fig. 4.20. A ^{109}Cd source was placed on the drift in position $i\phi = 2 - i\eta = 1$ and moved along the $i\eta$ direction. The results of the measurements are shown in Fig. 4.21a, where it is possible to see a drop of the anode current that indicates a non-working GEM amplification stage. By means of a comparison with the GEM foil layout, it was possible to localize the short-circuit on the third HV region of the 2nd GEM foil. Finally, to ensure the proper functioning of the detector region involved in the potentially destructive test, a similar scan along the $i\phi$ direction was performed. The results are shown on Fig. 4.21b. The measurement demonstrated that the $i\eta = 1$ column worked properly. The calibration of the discriminator threshold was performed, with the same method detailed in Sec. 4.3.1. The results are shown in Fig. 4.22.

From previous tests it was clear that a discharge could be triggered in any point

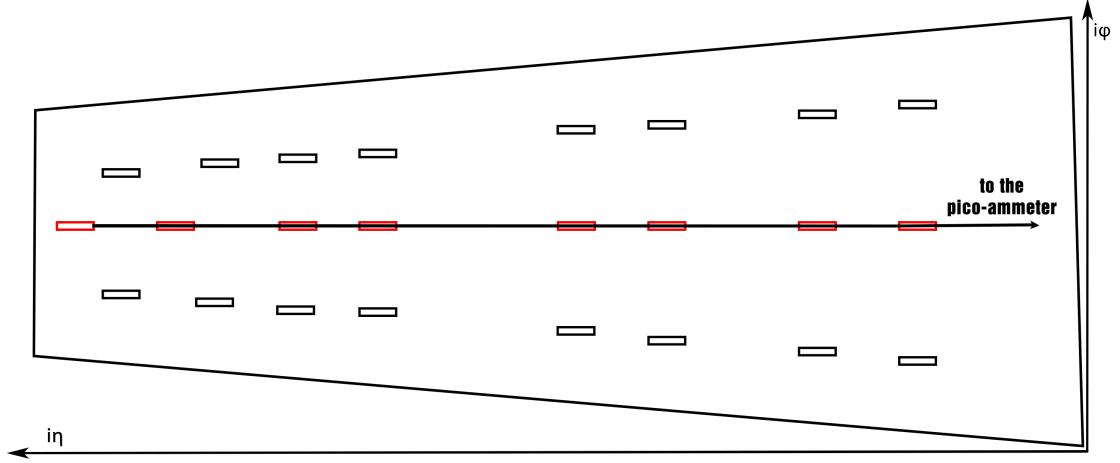
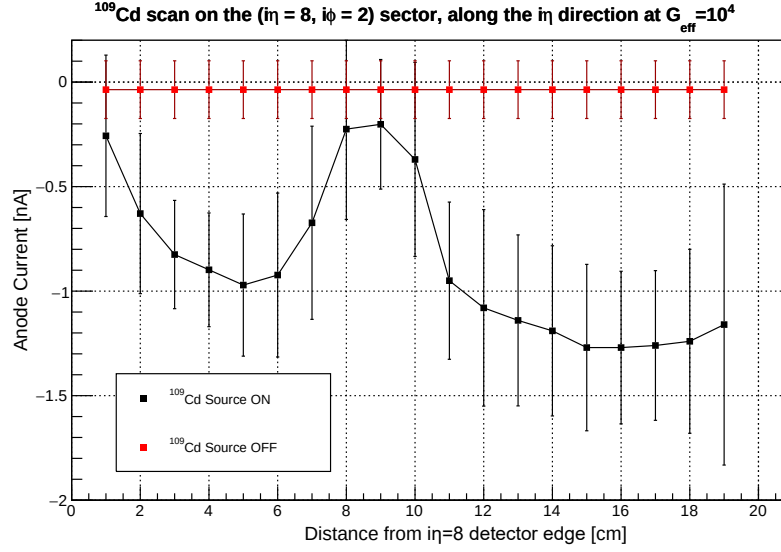


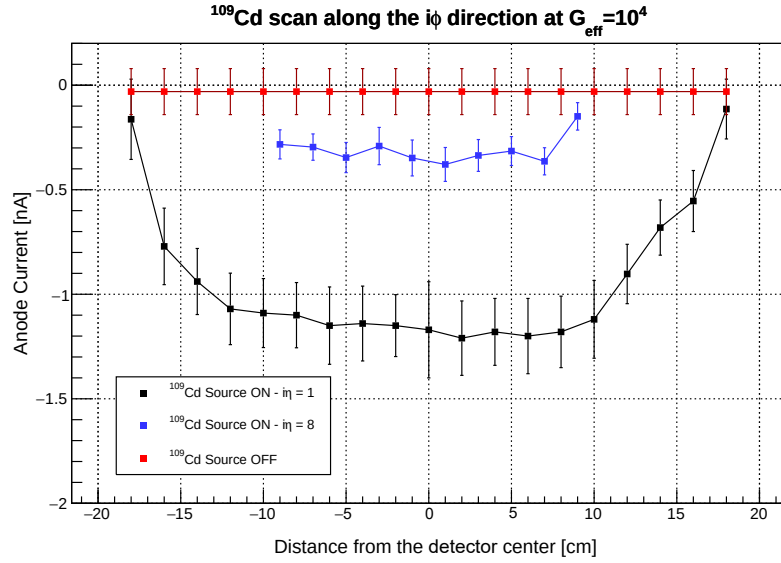
Figure 4.20: Sketch of the set-up for the scan with the ^{109}Cd . The rectangles represent the 24 readout connectors of the GE1/1 detector. In red, the connectors of the $i\phi = 2$ partition, in which the 128 strips have been OR-ed. These 8 readout partitions are then connected in series and the total current is finally read by a pico-ammeter. The 16 remaining readout partitions are terminated at 50Ω .

of the detector due to its HV instability, so one of the most important things to check were the illuminated strips. A beam profile measurement was performed, in order to localize the avalanche position on the readout. The beam profile was performed at $G_{\text{eff}} = 10^4$, by reading the data from the strips, using the fast trigger path of the VFAT (see Sec. 4.2.1). Due to the stopping power of the α -particles coming from the ^{241}Am , its beam reaches the drift gap only if it is aligned with the hole drilled in the drift board. Three different radiation sources were aligned with the drift board hole in correspondence of the VFAT 7 position: ^{241}Am , ^{109}Cd , ^{55}Fe . Fig. 4.23 shows a comparison between the beam profile of the three sources, normalized to have the same number of entries (different sources have different rates and will trigger avalanches of different sizes). The beam profile acquired, converted from detector strips to VFAT channels, showed that the selected hole corresponded to channels in the range (114, 128) on VFAT7. It is also possible to notice the differences in the beam profile between ^{109}Cd and both ^{241}Am and ^{55}Fe . Basically the particles coming from the two latter, are absorbed by the drift PCB, so the yield of electrons released in the drift gap is negligible, unless the emitted particle pass through the Mylar window. Therefore their beam profiles resulted collimated with the hole in the drift PCB. The ^{109}Cd is instead, is a mixed source of electrons and photons, with sufficient energy to produce a considerable electron yield in the drift gap.

In order to recognize the discharge events, the detector was instrumented with an *antenna* shown in Fig. 4.24a. The antenna was coupled with the HV cables

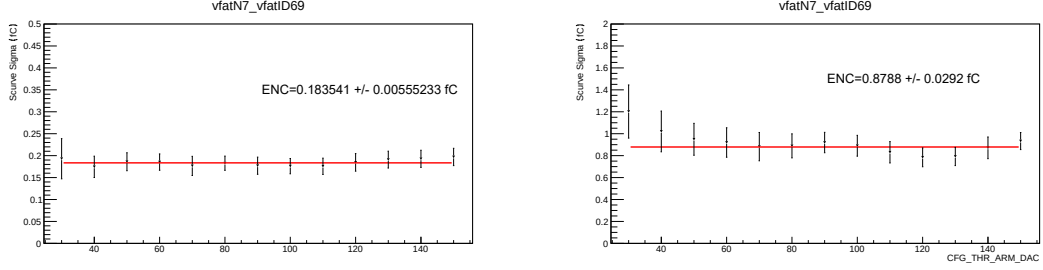


(a) Overall current read from the readout sectors of $i\phi = 2$ row, while the ^{109}Cd source was moved along the $i\eta$ direction.



(b) Overall current read from the readout sectors of $i\eta = 1$ and $i\eta = 8$ rows. The ^{109}Cd source was moved scan along the $i\phi$ direction.

Figure 4.21: ^{109}Cd scan on the detector in order to localize the short-circuited HV sector. The bottom plot shows that the HV sector in correspondence of VFAT 7 ($i\phi = 1$ - $i\eta = 1$) resulted to be properly working.



(a) VFAT7 average σ fit parameter vs discriminator threshold (b) ON Detector: VFAT7 average σ fit parameter vs discriminator threshold

Figure 4.22: Summary of the ENC for VFAT7 as a function of the discriminator threshold, both for the bare electronics and for the On-Detector configuration.

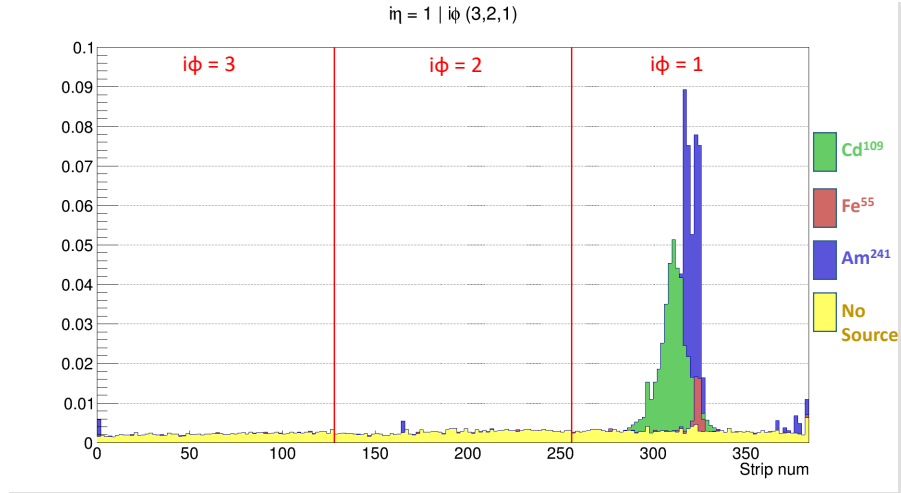


Figure 4.23: Beam profiles obtained with three different sources. The total number of entries is normalized to 1 for each dataset.

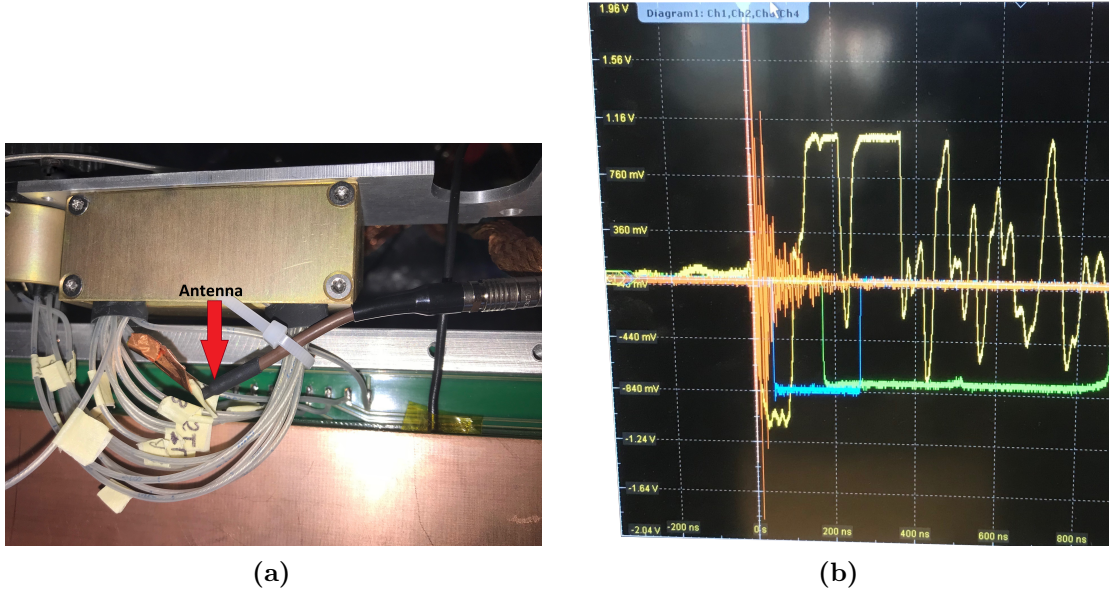


Figure 4.24: (a) Antenna coupled with the HV cables of the HV filter.
 (b) Scope screenshot of a discharge event. The orange signal shows the signal picked up by the antenna while the yellow one is the signal extracted from the GEM3 bottom electrode (distorted due to the saturation of the amplifier). In blue and green are reported signals used to trigger the discharge counters.

that fed the detector: each discharge event produced an EM pulse that induced a signal on the antenna. Moreover the signals from the GEM3 Bottom electrode were read. These two signals combined gave a strong signature of the discharge event (see Fig. 4.24b). Finally, the current limit on the HV power supply, did cause the shutdown of the detector, in case of an high current drawn, which characteristic of a discharge event.

The readout strips of the detector were terminated with $50\ \Omega$ in order to measure the discharge probability when the chosen hole position is exposed to ^{241}Am at $G_{\text{eff}} = 6 \times 10^4$. The ^{241}Am was held in a fixed *always On-Detector* position, shielded with paper sheet when no α particles were needed. The results are shown in Tab. 4.3. During the R&D phase of the GE1/1 project, the discharge probability

Table 4.3: Measurement of the discharge probability at $G_{\text{eff}} = 6 \times 10^4$ while all readout strips were terminated at $50\ \Omega$.

Tot. Time	α_s injected	Discharges	Disch. Prob. 68% CL
9435 s	5 M	3	$[2.7 \times 10^{-7}, 1.2 \times 10^{-6}]$

for a $10 \times 10\text{ cm}^2$ single-GEM (see Fig. 1.7) was measured at high gain and then

Table 4.4: Summary of the total number of injected α -particles at each G_{eff} , the relative number of discharges and the 99% confidence limit for the discharge probability evaluated with the Clopper-Pearson interval [58].

G_{eff}	α_s injected	Disch.	Disch. Prob. 99% CL
10^4	6 M	0	$\leq 8.8 \times 10^{-7}$
2.5×10^4	3 M	0	$\leq 1.8 \times 10^{-6}$
6×10^4	3 M	0	$\leq 1.8 \times 10^{-6}$
10^5	800 K	3	$[4.2 \times 10^{-7}, 1.4 \times 10^{-5}]$

extrapolated for low gain. These data were used as to estimate the time to be awaited for a discharge. However, as will be showed later on, the discharge probability does depend on the foil surface.

The results of the discharge probability measurement for a GE1/1 detector operated at $G_{\text{eff}} = 6 \times 10^4$ are in Tab. 4.3. Despite the low number of triggered discharges, the confidence level lies far outside the results obtained for the small triple-GEM in the CMS configuration (see Fig. 1.7). A deeper comparison carried out at higher gain points, would have helped in the confidence of such a result. However, since we were aware about the weakness of the second GEM foil, the measurements was ended.

In order to measure the probability of causing a damage on the front-end channels, the detector was instrumented with the VFATs, and the test was started. It consisted in:

1. power the detector at a known gain;
2. inject α -particles in the drift gap;
3. stop the α -particles after 10 minutes or any HV incident or discharge;
4. take an s-curve to monitor the healthiness of the channels;
5. Restart at a new G_{eff} point, after 3M α_s injected.

A summary of the performed test is shown in Tab. 4.4. The first discharge, obtained at a $G_{\text{eff}} = 10^5$ resulted in s-curves indicating zero passing events for all the channels of the VFAT 7 (see Fig. 4.25a). Differently, the remaining VFATs, had increased the average noise (see Fig. 4.25b), similarly to what we have seen after a discharge with the *Non destructive test* (see Fig. 4.15). The VFAT on position 7 was still controllable through the slow-control, which hints a damage only in the analog partd of the VFAT, probably in the calibration module. A close up showed two detached bonding wires (see Fig. 4.26), that corresponded to channels between

the 120th and the 128th, perfectly matching the beam profile.

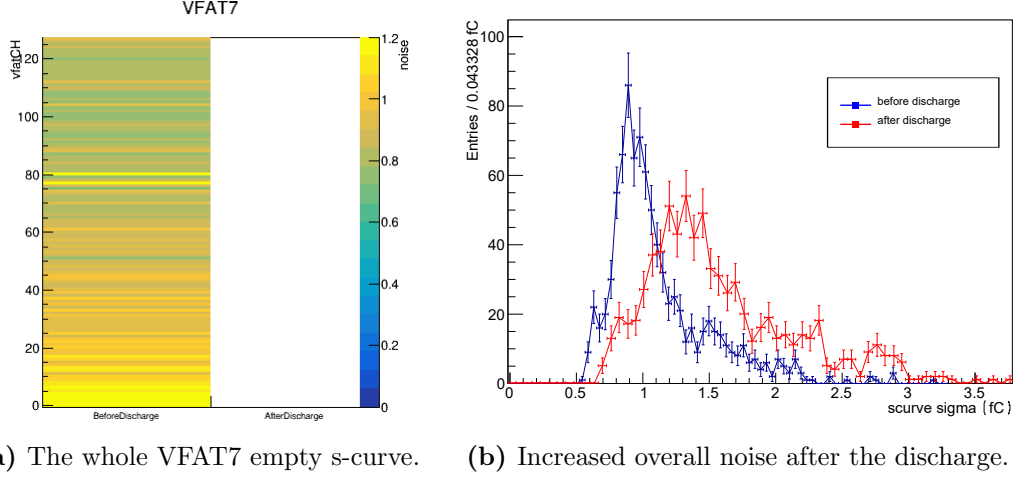


Figure 4.25: Electronics damage after one discharge at $G_{\text{eff}} = 10^5$. (a) shows the *Time Plot Series* that shows that all VFAT7 channels were non responding after the discharge. (b) shows the noise distribution for the average ENC over all the instrumented VFATs: in blue and red the noise distribution before and after the discharge respectively.

Two more HV events were triggered at $G_{\text{eff}} = 10^5$: the first one damaged the VFAT23, the second one damaged, in a single event, VFATs 5 – 6 – 7. Among the many proposed mechanism for discharge propagation in the induction gap (see Chap. 3), only the photon driven one may explain the damages 40 cm away from the α -irradiated cone. However, as showed before, this particular detector was unstable at high G_{eff} values, therefore these damages were probably induced by self-triggered discharges rather than photon driven discharge propagations.

The results obtained so far, gave some good suggestions on how to proceed. First of all working at $G_{\text{eff}} = 10^5$ helped to obtain discharges in reasonable time, but did not reproduce the realistic scenario in the CMS experiment because of the higher energy available in the induction gap due to the higher voltage. Moreover it caused the HV instability of the detector with uncontrolled discharges triggered outside of the beam profile area and cause shorts in the GEM foils. Secondly it pointed out a direct cause-effect correlation between discharges and channel loss on VFAT3. Lastly the oscilloscope screenshot, shown in Fig. 4.27, suggested that the time scale of a discharge is $T_{\text{disc}} \leq 100 \mu\text{s}$, much faster with respect to the automatic HV shutdown when the current limit is exceeded. It also showed that two processes were involved in a discharge, separated by $\simeq 10 \mu\text{s}$. The first antenna trigger lasted $\leq 100 \text{ ns}$, accompanied with a fast rising up of the GEM3 bottom signal up to the saturation level of the amplifier. Then, after $\sim 3 \mu\text{s}$ from the first antenna trigger, a larger and longer lasted signal was induced on the antenna. The GEM3 bottom signal showed an oscillating pattern between the staturation levels.

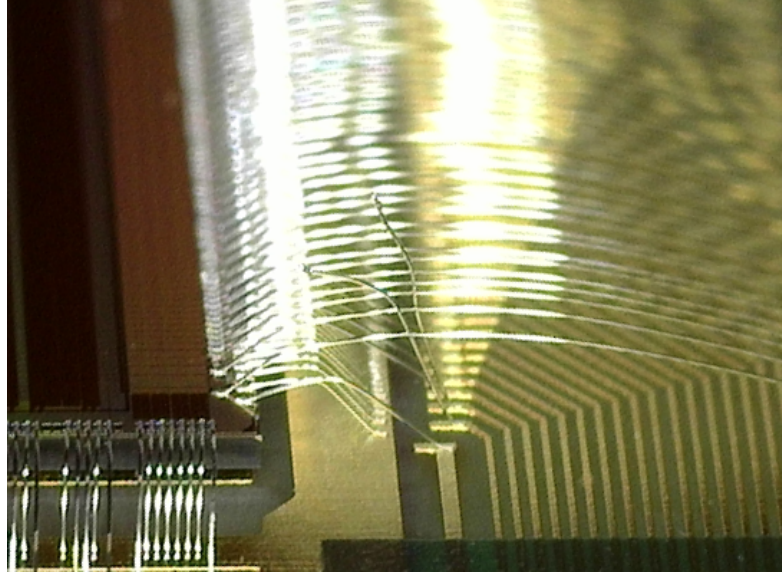


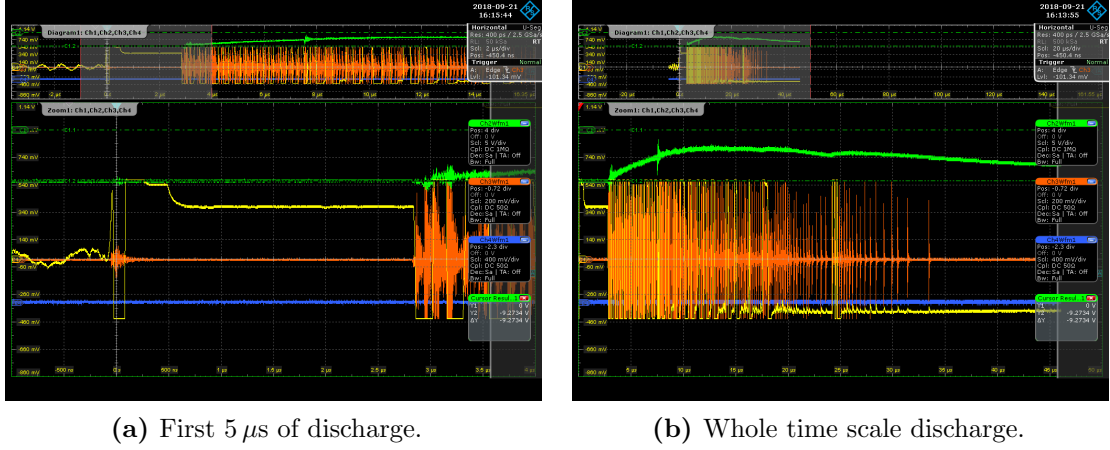
Figure 4.26: Detached bonding wire afterwards the discharge event at $G_{\text{eff}} = 10^5$.

The whole process lasted $\sim 30 \mu\text{s}$.

The interpretation of this event can be the following: the first antenna trigger corresponds to a discharge inside the GEM foil, most likely the GEM3 due to the fluctuations in the GEM3 bottom signal. The second antenna trigger is a much longer signal, and as discussed in Chap. 3, it can be related to a discharge in the induction gap. This hypothesis is also supported by the damages we have seen on the front-end electronics after this event. These results stated that propagated discharges are the cause of channel loss.

4.3.3 Probability of Propagating discharges

The propagation probability has been defined as the ratio between the discharges that propagate in the induction gap and the primary discharges triggered in the GEM foil. The mechanism that originates the propagated discharges is not yet understood, a possible one is discussed on Sec. 3.4. At the moment of the study, it was ascertained that propagated discharges are always preceded by an initial discharge, and the propagation takes place only if the induction field is higher than a threshold value. Since stopping the propagation meant stopping the damage on the readout electronics, measurements of the discharge probability on a GE1/1 detector have been performed, using the double structure in the antenna signal as a signature for propagating discharges. Finally an analogous measurement was carried out on a $10 \times 10 \text{ cm}^2$ triple-GEM in order to make a comparison. The results shown in Fig. 4.28 highlight a different trend in the propagation probability between the small detector and the GE1/1 one. While for the small detector the trend is the one characteristic of a threshold dominated process (e.g. the s-curve

(a) First 5 μs of discharge.

(b) Whole time scale discharge.

Figure 4.27: Scope screenshot of one discharge at $G_{\text{eff}} = 10^5$. The antenna signal in orange while the GEM3 Bottom AC signal in yellow. It can be notice the devolving of a *secondary discharge* after $\simeq 3 \mu\text{s}$ from the first antenna trigger.

discussed in Sec. 4.2.1), on the GE1/1 detector the propagation probability is flat and does not reach 100 % even when the induction field doubles the designed value of 4 kV/cm. Therefore we have to be aware of the differences in the propagation probability as the GEM foils scale up from $10 \times 10 \text{ cm}^2$ to the GE1/1 detector. A conclusive proof will be conducted on a large GEM foil with the bottom electrode segmented, in order to replicate the small triple-GEM setup. This is a possible mitigation strategy, however we still lack of explanation about the motivation for such different behaviour.

As discussed in Chap. 3 the secondary discharge is also preceded by a precursor current in the anode plane that has not a voltage counter part. Therefore the origin of such a current has to be searched in the charge carriers involved in the secondary discharges. The rise of the current on the anode before a discharge, suggests a possible mitigation strategy. Applying a drain resistor between the readout plane and the ground would cause a rise of the anode voltage as the induced current pass through it. The induction field would then be reduced and the carriers flow slowed down with mitigation effects in the discharge propagation. This idea has recently been implemented in a custom VFAT hybrid plugin, named *Sandwich Board*, which has a 100 k Ω drain resistor between the strip and the ground and a decoupling capacitor to the VFAT channel input. A preliminary measurement of the propagation probability at $E_{\text{ind}} = 4.1 \text{ kV/cm}$ with the VFAT instrumented on the *Sandwich Board*, showed good improvements, with a 68% CL for the propagation probability equals to [0.13, 0.25], to be compared with the [0.65, 0.75] of the standard GE1/1 design. The main down effect of such an implementations regards the signal loss due to the drain resistor that might affect the detection efficiency. Further

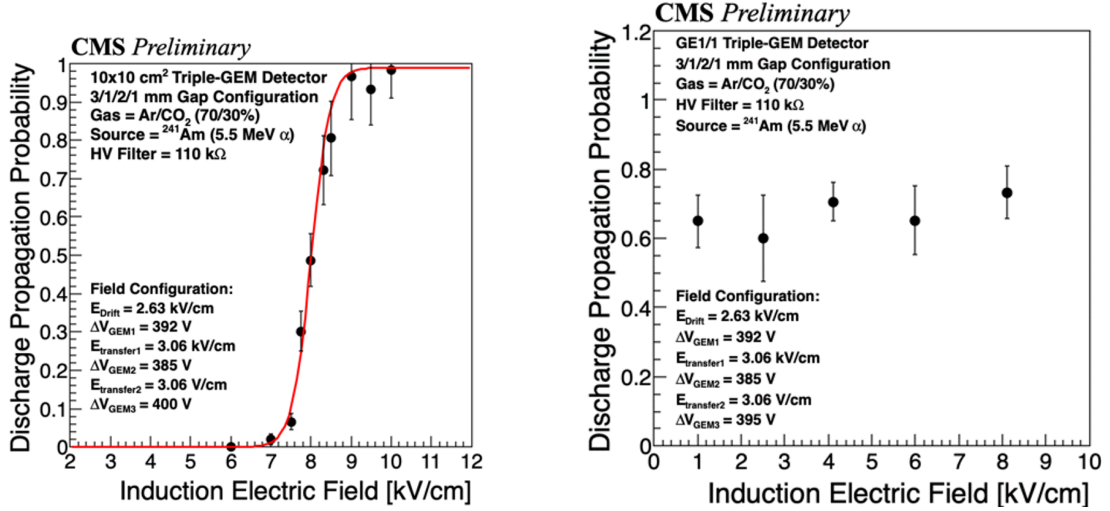


Figure 4.28: On the left the propagation probability for a $10 \times 10 \text{ cm}^2$ triple-GEM detector. On the right the propagation probability for a GE1/1 triple-GEM detector.

studies are needed to fully characterize the *Sandwich Board* and find the optimum values for the drain resistance and the input capacitance with respect to propagation probability, damage probability and signal loss.

4.4 Toward Mitigation Strategies

Further investigations on the electronics hardness and studies of discharges in GEMs detectors are detailed in the following paragraphs. The aim was the reduction of the hazard of the discharge processes (e.g. reduce both propagation and damage probability). From the front-end point of view the key parameter is the energy released on the strips rather than the detector gain, evaluated as $E = 1/2CV^2$.

4.4.1 New Hybrid schema

The capacitance between the GEM3 bottom electrode and the readout strips was calculated and measured for a detector *not* instrumented with the electronics, the HV filter nor the cooling system. It resulted $C_{\text{ind}} = 2.8 \text{ nF}$ in both cases. However due to the capacitive coupling with the GEB, the cooling and the HV filter, the same measurement on a finished detector resulted $C_{\text{ind}} = 10.1 \text{ nF}$, leading to $E_{\text{disch}} = 0.9 \text{ mJ}$. Finally, in order to trigger discharges at $G_{\text{eff}} = 10^4$ (see Fig. 1.7), the ΔV between the top and the bottom electrode of the GEM3 foil was raised to 395 V very close to the Raether limit (see Sec. 3.2.1), which is obviously not the value it was designed for.

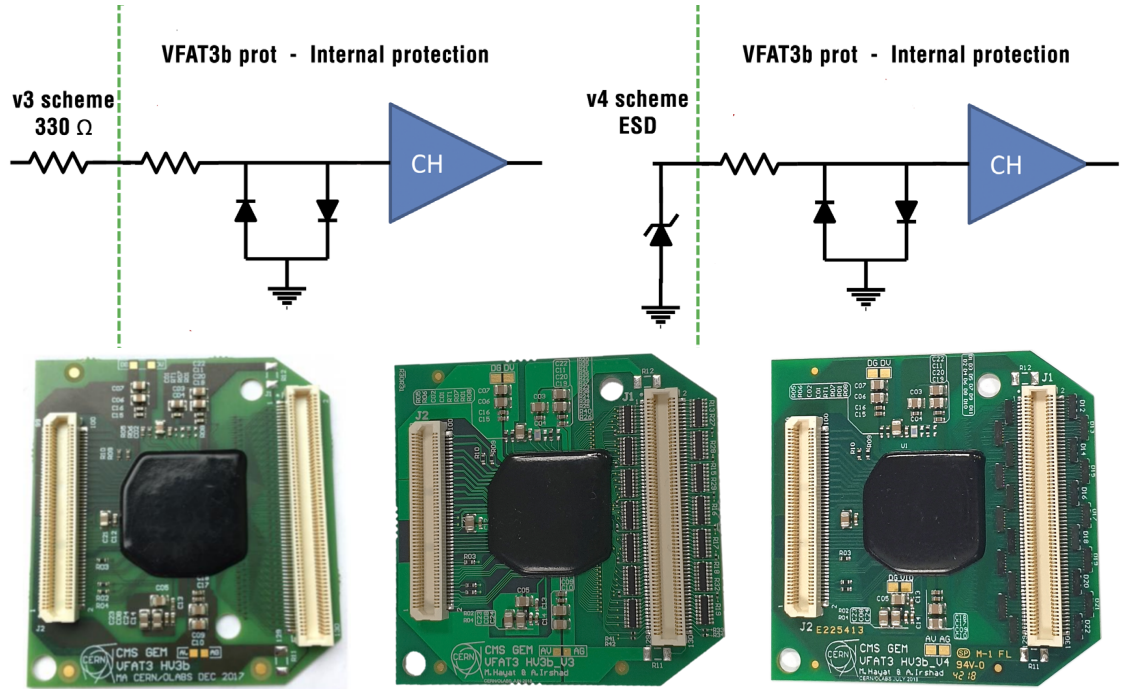


Figure 4.29: On the top a single channel input of the enhanced hybrid schema v3 and v4 [59]. On the bottom, from left to right, hybrid v2,v3 and v4. Close by the larger white connector can be noticed the different installed components.

The electronics team (in Bari) proposed and tested two solutions to improve the channel spark protection, showed in Fig. 4.29. They were designed to be implemented on the hybrid plugin board with a bounded VFAT3 chip and named hybrid v3 and v4 respectively. The v3 scheme involved an external resistor on the channel input, whose value, after preliminary tests on the bench, was chosen to be $330\ \Omega$ [60]. A gas discharge tube was used to inject high charges on a selected channel with controlled voltage and energy. A discrete $330\ \Omega$ resistor was installed on the channel input of a standard hybrid (v2), and after 500 discharges at 460 V with $E = 1/2 \times 4.47 \times (460)^2\ \text{nfV}^2 = 437\ \mu\text{J}$, the channel was still properly working. The measurements on the bench, stated that the external protection resistor increased the ENC by 13 – 36% with respect to the standard v2 version, depending on the input capacitance. Furthermore the higher input impedance worsened the cross talk between channels¹. The simulations performed stated that the cross talk between channels increased from 3.4% to 14.5% when the $330\ \Omega$ protection resistor is added to the input circuit. The v4 protection scheme involved an ESD on the channel input and showed negligible increase in noise and cross talk, with the channel still working after 500 discharges at 460 V with $E = 437\ \mu\text{J}$.

The degradation process of the protection resistor installed on a prototype of

¹it is the fraction of the injected signal on the channel X that is detected by X's adjacent channels.

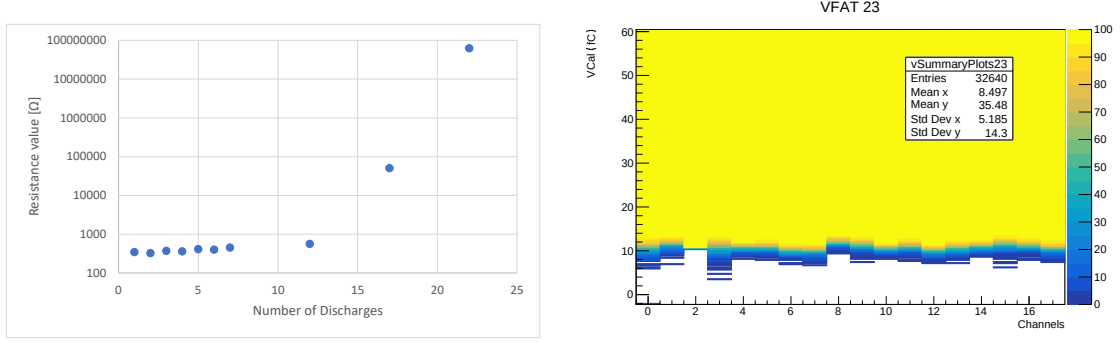


Figure 4.30: On the left the resistance value of the the v3 hybrid protection input placed on the channel 2, as a function of the number of discharges triggered on the test bench device. The discharge was injected with energy set to 0.862 mJ to match with the energy estimated on the GE1/1 detector. On the right the s-curves taken on the VFAT23 channels after many discharge injections. As can be seen the channel 2 manifests a much lower ENC.

hybrid version 3, has been put under investigation. The goal was to improve the hardness of the protection resistor and gather a better understand of the processes that led to detached channels. The test was conducted with one VFAT connected to the GEB, while one of its channel input was connected to custom discharge device made in Bari. It consisted of an RC circuit with swappable capacitors, connected to a gas tube that produced a discharge whenever the voltage on the capacitor reached a threshold. Since the gas tube output was connected directly to the VFAT3 channel input, the full control on the injected charge and the injected channel was ensured. The channel integrity was checked with the s-curve routine. Fig. 4.30 shows the resistance value of the hybrid resistor placed on channel number 2. As the number of discharges increases, the resistance increases till it reaches values of $\sim M\Omega$, at which the channel has an ENC that suggests the detachment from the relative detector strip. Furthermore the increase of the resistance worsens the electronics performance (ENC and cross talk) as explained previously. These results and those coming from a previous study conducted in Bari, suggested to increase the protection resistor in size and magnitude to enhance the capability of energy dissipation. The team chose to produce hybrid v3 with 470Ω resistor.

4.4.2 Destructive test

A parallel test was conducted on a triple GEM in the CMS configuration, with $10 \times 10 \text{ cm}^2$ GEM foils, read with a single VFAT. The damage probability was measured on this set-up for hybrid versions 2,3 and 4. The $10 \times 10 \text{ cm}^2$ detector was operated at $E_{\text{ind}} = 9 \text{ kV/cm}$ to ensure the propagation of discharges to the readout board (see Fig. 4.28), while the discharge energy was changed by adding capacitors in parallel to the induction gap. The results are shown in Fig. 4.31. The

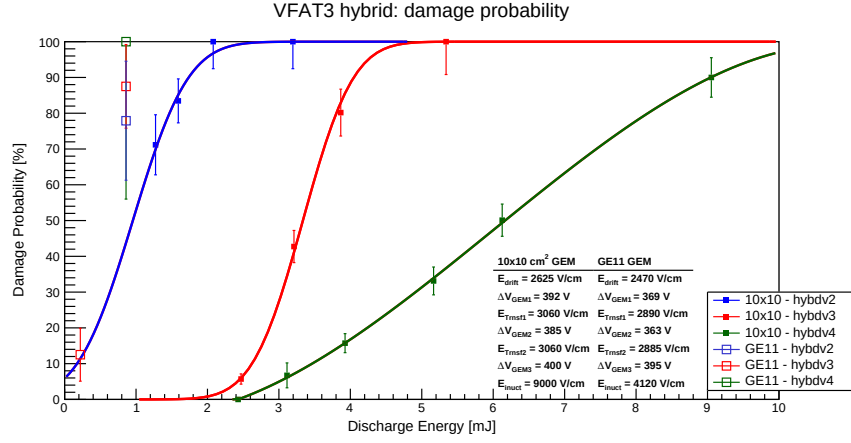


Figure 4.31: Damage probability comparison for hybrid v2,v3 and v4 instrumented on a $10 \times 10 \text{ cm}^2$ GEM detector in the CMS configuration and on a GE1/1 detector. For the GE1/1 detector the discharge energy was set by changing the electric field in the induction gap. To avoid unnecessary detector damages, the GE1/1 test was abruptly with fewer energy points.

plot shows that the energies at which the damage probability results to be 50%, are 1, 3.1 and 6 mJ for hybrid versions 2,3 and 4 respectively, suggesting the v4 as the best solution to be implemented.

The same test was conducted on a GE1/1 detector. The GE11-CERN-X-L-0002 effective gas gain was measured in correspondence of the VFAT15 position and an ^{241}Am beam profile was performed. The detector was operated at the designed operational gain of $G_{\text{eff}} = 10^4$, voltages shown on Tab. 4.5. The voltage on GEM3 was pushed to 395 V, in order to achieve an electron yield close to the Raether limit (see Sec. 3.2.1) and trigger primary discharges inside the 3rd GEM foil. The energy stored in the induction gap, evaluated as a parallel plane capacitor, corresponded to 0.86 mJ, however the induction field was adjusted later on to lower the discharge energy. The signals from the antenna and the AC coupled GEM3 bottom, were sent as inputs to the scope, as done previously. Among all the discharges triggered throughout the test, the ones with single antenna events (shown on Fig. 4.32a) did not cause any channel loss, while structured antenna signals like the one shown in Fig. 4.32b, did damage the channel with a certain probability. The results are shown in Fig. 4.31. The large error bars are a consequence of the low statistics collected. In fact, due to the HV instability, the number of total discharges was limited in order to preserve the detector operation. Furthermore, since the number of available version 4 hybrid boards was limited, the relative statistics is the smallest, resulting in the largest error bars.

The GE1/1 detector did not reproduce the results found with the $10 \times 10 \text{ cm}^2$ setup, for both damage probability and propagation probability. The hybrids v2 and v3 exhibited the damages limited to one-few channels, either with low ENC

Table 4.5: The voltage differences and the electric fields in each gap of the GE11-CERN-X-L-0002 for the damage probability measurement.

	Drift	GEM1	Tran1	GEM2	Tran2	GEM3	Ind
ΔV (V)	742	369	289	363	577	395	412
E (kV/cm)	2.5	73.8	2.9	72.6	2.88	79	4.1

**(a)** Discharge that doesn't propagate to the readout board.**(b)** Discharge that does propagate to the readout board.**Figure 4.32:** Comparison for the Antenna+GEM3 Bottom AC signals between propagated and non propagated discharge. In orange the signal picked up by the antenna while in yellow the signal extracted from the GEM3 bottom electrode. The signal in green was used for triggering reasons.

(disconnected channel) or an empty s-curve. Differently, the v4 hybrids tested on the GE1/1 detector have been damaged in such a way that empty s-curves were measured for all the VFAT channels, and not only the channels, identified with the beam profile, being irradiated (see Fig. 4.33). This may be caused by a damaged calibration module, not able to deliver calibration pulses to the channel input. Unfortunately this hypothesis could not be confirmed experimentally because of lack of time to take the final decision on which VFAT3 hybrid board to choose for final detector production.

4.4.3 Mitigation Strategies

The tests detailed so far returned totally different results between the $10 \times 10 \text{ cm}^2$ setup and the GE1/1 detector, suggesting that the physics processes involved are pretty different as the detector size is scaled up. The type of damages seen for hybrid v4 on the GE1/1 detector, could be explained with a voltage difference between

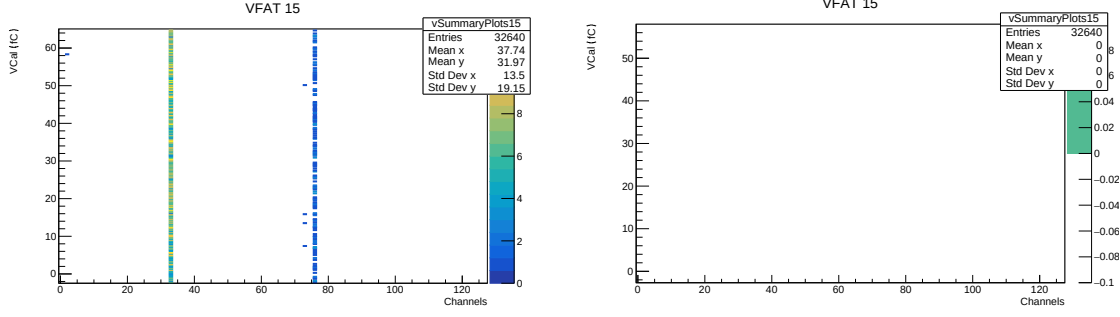


Figure 4.33: s-curves for the irradiated VFATs with hybrid v4, after one propagated discharge on a GE1/1 detector.

the analog and the digital ground of the VFAT on the GE1/1 setup, due to the presence of the GEB. In fact, the large amount of current coming from a discharge, activates the ESD protection and goes across the whole GEB analog ground path before reaching the ground. Therefore even a small value of the resistivity on the path to ground, could cause a $\Delta V_{AG-DG} > 100mV$, higher than what VFAT3 can handle. Since hybrid version 2 and 3 do not have the ESD protection connected to the analog ground, this hypothesis is consistent with the different damages observed. In order to decouple the GEB related effects from the detector effects, the VFAT instrumented on the $10 \times 10 \text{ cm}^2$ detector was connected to the GEB. The electric field in the induction gap was set to 8000 V/cm and with the added parallel capacitors, the stored energy in the induction gap was $\frac{1}{2}CV^2 = 0.864 \text{ mJ}$. The damage probability measured for the v4 hybrids was 0%, reproducing the measurement previously done with the $10 \times 10 \text{ cm}^2$ detector not instrumented with the GEB. An additional test was conducted with the GE1/1 detector instrumented with a customized hybrid version 4; basically one hybrid v4 was modified in order to provide a low impedance path to ground and a shortcircuit between the analog and the digital ground see Fig. 4.34. This tests still gave empty s-curves for all the VFAT channels. Therefore the hypothesis of the ΔV_{AG-DG} as the cause of the damages seen for the hybrid v4 instrumented on the GE1/1 detector was ruled out. The behavior of the hybrid version 4 remains unexplained. Since it was much less reliable than the other versions, for the foreseen 10 years of lifespan, the hybrid version 4 was definitively rejected for installation in the GE1/1 project.

With the goal of reducing the available energy during a discharge, all the 2.2 nF capacitors on the HV filter (see Fig. 4.39) were removed from the detector GE11-X-L-CERN-0002. It was instrumented with a full GEB, OH, and a set of 24 VFAT3 hybrid version v2. Hence the capacitance between the GEM3 bottom electrode and the readout board was measured. The detector was operated at the voltages detailed on Tab. 4.5 and both the propagation probability and the damage probability were measured. Then the VFAT15 position was instrumented with a VFAT3 hybrid v3 while the rest of the setup was left the same. The propagation probability and

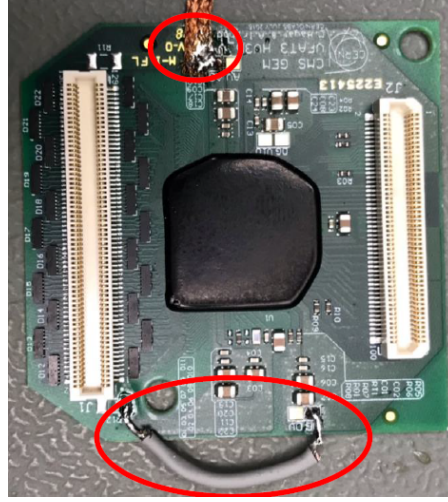


Figure 4.34: Picture of the hybrid version 4 board customized. The top ellipse highlights the copper tape that provides a low impedance path to ground. The bottom one highlights the short circuit between the analog and the digital ground of the ASIC.

Table 4.6: Damage probability and propagation probability at 68% confidence level after removing *all* the 2.2 nF capacitors from the HV filter, for hybrids version 2 and 3.

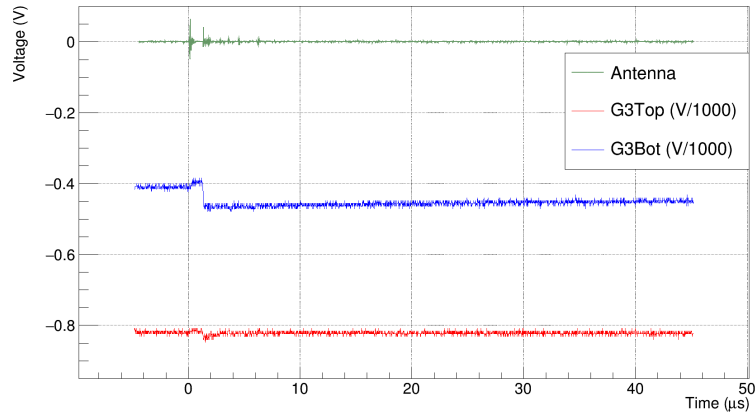
Hybrid	C_{G3B-RO}	Energy	Prop. prob.	Damag. prob.
v2	4.4 nF	373 μ J	[33%, 51%]	[53%, 81%]
v3	4.4 nF	373 μ J	[62%, 82%]	[15%, 40%]

the damage probability were measured again and the results are summarized on Tab. 4.6, where the confidence intervals for the binomial distributed parameters have been evaluated with the Clopper-Pearson interval [58]. The results shows a good improvement with respect to the results obtained in the standard HV filter configuration. A possible interpretation is that the HV filter capacitors released the stored energy during a discharge, firing the foil electrodes, so that it sustained the discharge instead of quenching it. This hypothesis can be tested using decoupling resistors on the HV filter in order to change its RC time. The standard value is 22 μ s which is comparable to the time scale of secondary discharges documented on Sec. 3.4.2, hence it has to be pushed to higher values. However the differences with the $10 \times 10 \text{ cm}^2$ setup (see Fig. 4.31) still hold, hence the larger electrode size may also contribute to the process and this is something that is not fully understood yet.

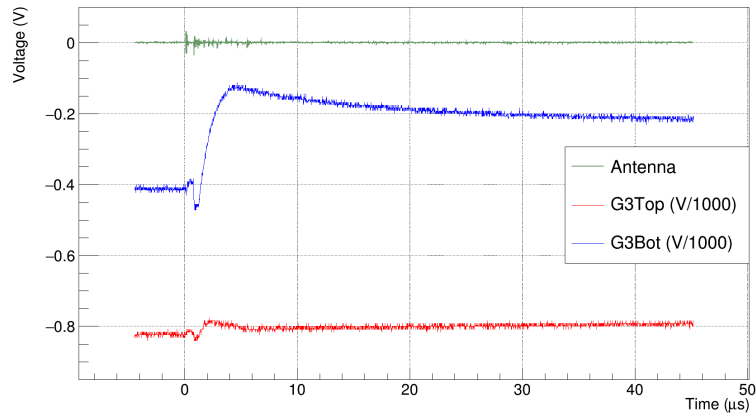
The physics processes involved during a discharge have been put under investigation, starting from the studies in Sec. 3. Two HV probes 1 $\div$ 1000 have been

connected to the GEM3 HV pads, in order to deeper understand the discharge process and the differences between HV filter with or without the capacitors. At the same time the damage probability was measured on the enhanced v3 hybrid (from now on referred as v3 470 Ω). Fig. 4.35 shows three different types of discharges that have been observed on a GE1/1 detector with the standard HV filter. On Fig. 4.35a there is a first trigger of the antenna (orange) on what may be interpreted as a discharge in one of the not monitored GEM layers; 1 μ s later there is a short in the GEM3 foil, with the bottom electrode voltage (green) that approaches the top electrode (magenta). The event does not involve propagation to the readout, and as already stated, no damages have been observed in such a event. Fig. 4.35b shows a similar event, with propagation of the discharge in the induction gap. First the GEM3 bottom electrode voltage increases to match the top potential, thereafter it decreases to go towards the same potential of the anode. These type of events have been found not to be the main source of channel loss: in fact the only occurrences of damages were recorded after a cumulative dose of discharges. Fig. 4.35c shows a much complex pattern. At the beginning the discharge develops as in the previous cases. However during the propagation in the induction gap, the GEM3 top electrode voltage drops to the bottom potential, evidently indicating a discharge inside the 3rd GEM foil. The phenomenon repeats several times, until the bottom voltage goes again toward the value of the anode (GND) associated with an huge antenna signal: the event has been named *reignition* and has been also observed in other studies (Sec. 3.4.2). We have to be aware about two facts. Firstly, the HV prpbe connected on the GEM3 top, is measuring the voltage on its relative pad located on the detector HV circuit. This means that between our probe and the GEM electrode there is a 10 M Ω resistor as described in the design [54]. Therefore the GEM3 top voltage read by the probe is affected by the voltage drop on this resistor. Secondly between the pad located on the detector HV circuit and the HV filter capacitor, there is a 10 k Ω resistor. These two processes cause a distortion of the actual voltages on the electrode, with respect to the voltages on the pad. Despite of this, the voltage measurement still gives enough information to propose a mechanism to explain the damgaes on the VFAT channels, discussed later on.

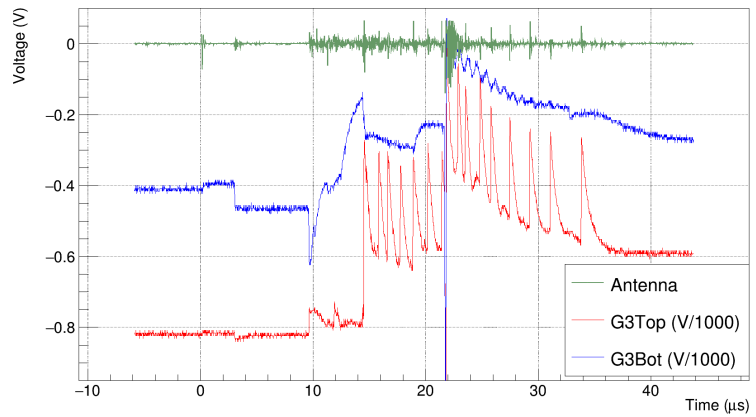
Th event type shown in Fig. 4.35c, has been correlated with channel loss on brand new channels and it has a more complex structure with respect to the reignited discharges observed on the 10 $\times$ 10 cm² detector. Removing the HV filtering capacitors, helped in the mitigation of discharge *reignitions*. In fact Fig. 4.36a shows an example of the HV time-evolution for the GEM3 electrodes when no capacitors were installed in the HV filters. As can be seen, after the progation of the discharge in the induction gap, the GEM3 bottom voltage (green) goes again toward the GEM3 top voltage indicating a discharge inside the GEM 3 foil. However this time no reignition in the induction gap were triggered and consequently the damage



(a) Single structure non propagating discharge.



(b) Single structure discharge followed by a propagation toward the read-out board.



(c) Single structure discharge followed by a multiple propagation toward the read-out board.

Figure 4.35: Scope signals of three different discharges types with the standard HV filter. The antenna signal (yellow) was used to trigger the scope. The GEM3 bottom (green) and the GEM3 top (magenta) HV probes monitored the voltage on the GEM3 electrode

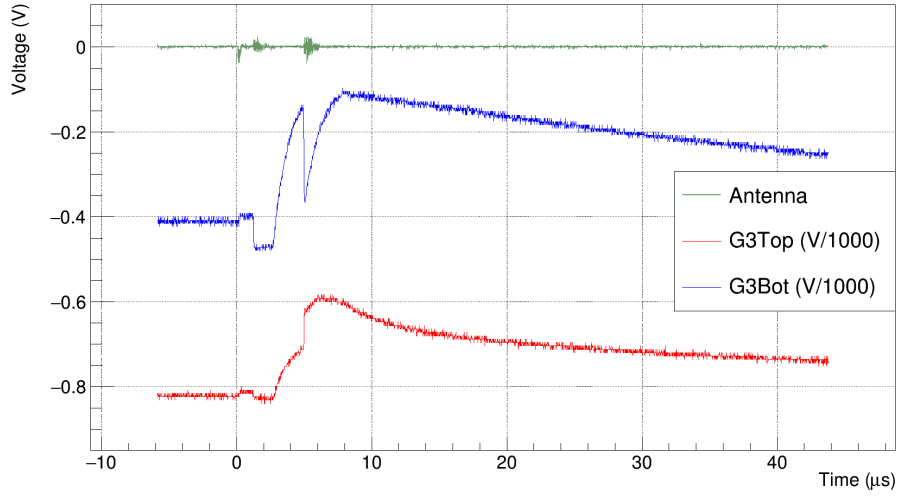
probability was drastically reduced (configuration 5 in Fig. 4.37).

A possible explanation of the event in Fig. 4.35c is the following: it is reasonable that once the discharge is propagated in the induction gap, the GEM3 bottom electrode approaches 0 V, while the GEM3 top electrode is quickly recharged at the normal voltage due to the segmentation. Hence the field inside the GEM3 reaches much higher values with respect to the operation design. At this point the Raether limit is easily exceeded and a discharge is triggered in the 3rd GEM foil. The energy stored in the filtering capacitors quickly restores the voltage on the GEM3 top electrode. Once again the segmentation on the GEM3 top foil limits the sector involved in a discharge to one, which is the sole that has to be *recharged*. The bottom electrode instead is not segmented, so it requires much more energy to be fully recharged, which results in a longer recovery time. Let us assume that the amount of charge on one electrode is $C = QV$, where $C \propto A/d$. The GEM foil bottom electrode surface area is $\sim 4000 \text{ cm}^2$ while each sector of the top electrode is $\sim 100 \text{ cm}^2$ large. Thus to fully recharge the bottom electrode, we need 40 times more charge with respect to what is needed to recharge the top electrode segment, $Q_b = 40 \times Q_t$. Therefore, assuming that the power supply can provide the same current for both layers, it is reasonable to foresee a ratio of 40 between the bottom and the top electrode recovery time.

Due to its shorter recovery time, the GEM3 top electrode keeps on discharging on the GEM3 bottom electrode, quickly heating the electrode. After six discharges inside the GEM3 foil, there is a reignition of the discharge in the induction gap: a new large signal is induced on the antenna and the bottom electrode goes toward 0 V again. At this point, the potential difference between the two electrode keeps on triggering discharges inside the GEM 3 foil, with a rate that decreases on time (the time distance between discharges goes from $\sim 1 \mu\text{s}$ to $2.5 \mu\text{s}$ as the bottom electrode voltage is recovered).

This explanation is also consistent with another observational evidence. Removing all the capacitors from the HV filter did reduce the damage probability, while decoupling only the bottom foil electrodes from the HV capacitors did not reduce the damage probability (see configuration 6 and 12 in Fig. 4.37). Therefore this interpretation suggests that the size of the electrode plays a role not only in the amount of energy available during a discharge, but it is also relevant when it comes to the recovery time and the discharge re-ignition. A segmented bottom foil would cause the top and bottom electrode voltages to recover simultaneously, quenching the reignition of the discharge. Moreover the segmented bottom foil will reduce the energy released due to a discharge, because of the reduced capacitance involved. Following this idea, a new prototype of GEM foils with segmented bottom electrode were assembled and tested. The results are in the Sec. 4.4.4.

Despite removing all the filtering capacitor gave very good results on the damage probability (see Fig. 4.37), it would nullify the filtering of the HV noise and would



(a) No filtering capacitors.

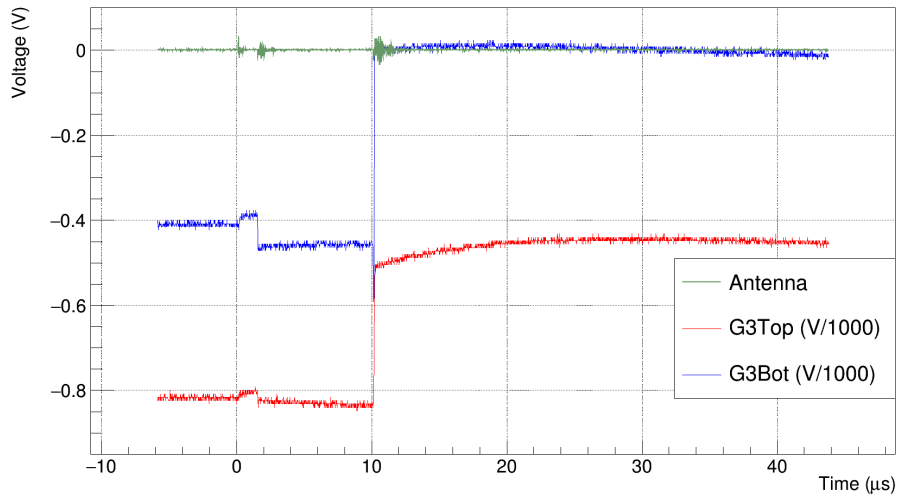
(b) 1 M Ω decoupling filter.

Figure 4.36: On the top the typical GEM3 voltages during a discharge without the HV filtering capacitors. During the propagation of the discharge in the induction gap, a discharge is triggered in the foil due to the increased field. However no discharge reignition is triggered and the GEM3 top voltage is recovered after $\simeq 100 \mu\text{s}$. On the bottom the typical GEM3 voltages for the 1 M Ω de-coupling resistor in the HV filter: no reignitions

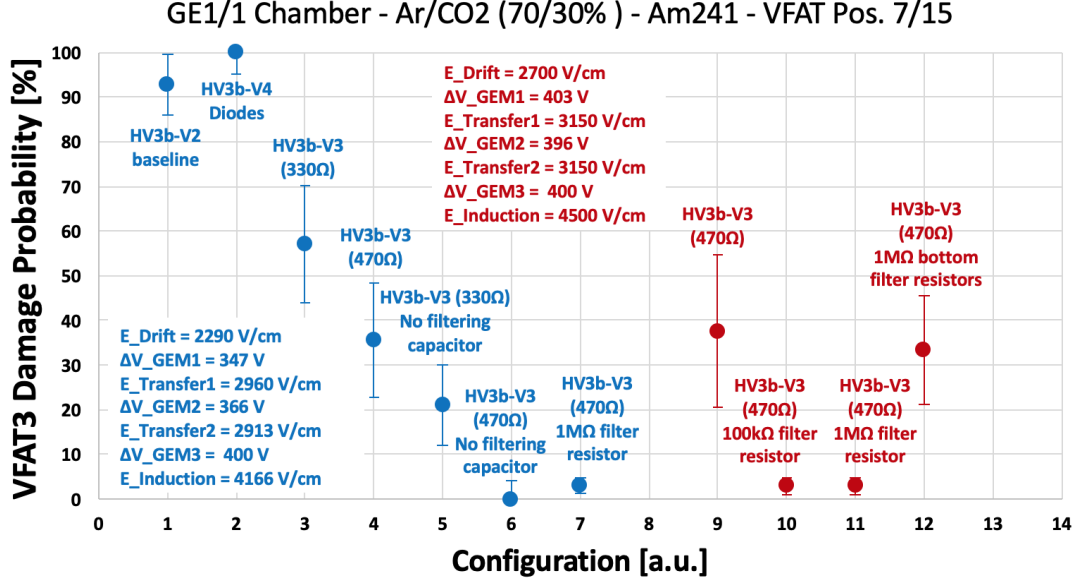


Figure 4.37: Comprehensive summary of the damage probability measured for all the VFAT3 hybrids tested. Blue points refers to low gain measurements, while the red points refers to higher gain. Where is no specification is given, the configuration refers to a GE1/1 detector with the design HV filter.

change the approved design of the GE1/1 detectors. Therefore it has been chosen to decouple the filtering capacitors from the detector, by increasing the 10 k Ω resistance that faces the detector (see Fig. 4.39). Both the 100 k Ω and the 1 M Ω implementations were tested with very promising results either for stopping the reignition (see Fig. 4.36b) and for the damage probability (see Fig. 4.37). However the change in the HV filtering resistor may cause a drop in the rate capability hence for both resistor value the rate capability was measured (see Sec. 4.5.1).

Fig. 4.37 shows a summary of all the measurements done for the damage probability on GE1/1 detectors for two sets of voltages. It is possible to see how the damage probability was stepwise reduced with the progression of the configurations. The v3 470 Ω was proven to be much reliable with respect to the v3 330 Ω . Additionally decoupling all the HV capacitance from the GEM foil electrodes, helped preventing the discharge reignitions and therefore the damage probability, while decoupling only the bottom layers did not.

The best results are obtained with configurations 10 and 11, in which, despite the higher operational voltages the damage probability stays very low and, at the same time, the HV filter capacitors grant the filtering of the noise. The plot also shows the remarkable result obtained: the improvements introduced reduced the damage probability from the $\sim 92\%$ of the configuration 1 to the $\leq 5\%$ of configurations 10 and 11.

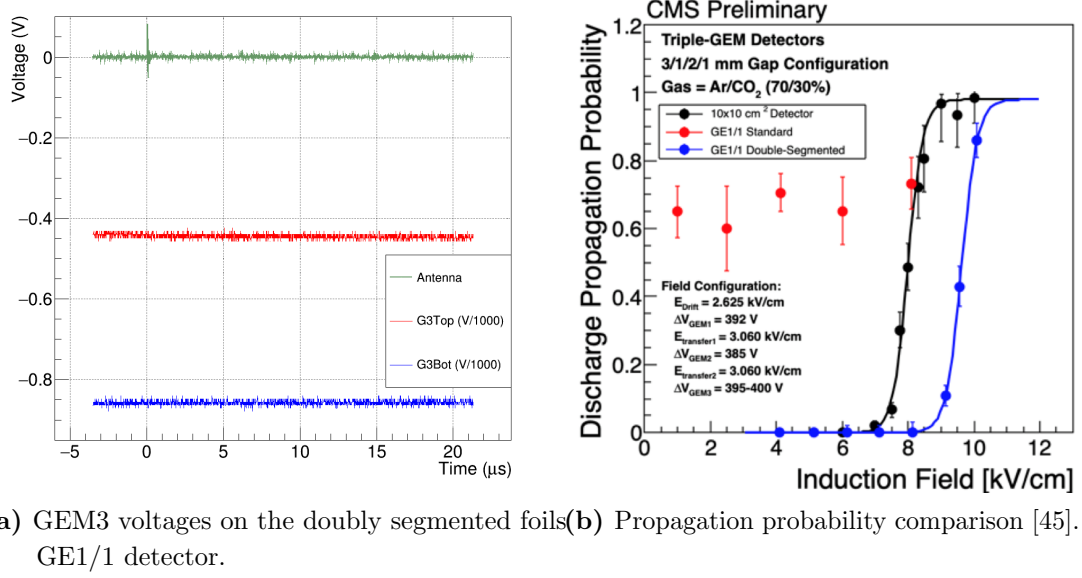


Figure 4.38: On the left the typical GEM3 voltages during a discharge in the GE1/1 detector assembled with the doubly segmented foil. On the right a comparison for the discharge propagation probability between $10 \times 10 \text{ cm}^2$, standard GE1/1 and doubly segmented foils GE1/1.

4.4.4 The Doubly Segmented Foils

Triple GEM detectors with the very same design as GE1/1 will be used to instrument station GE2/1. Even if the design is geometrically different, the readout system will follow the same GE1/1 DAQ scheme. In order to enhance the mitigation of discharges, a new GEM foil prototype has been proposed based on the studies performed for the discharge mitigation of the GE1/1 detectors. In this new design, the bottom electrode of the GEM foil has been segmented identically to the top foil. The studies performed on the standard GE1/1 detector suggested that large GEM detectors do not behave as the $10 \times 10 \text{ cm}^2$ prototype when it comes to discharge propagation, because of the large amount of charge storable in the bottom electrode. Furthermore for the reasons explained in the previous sections, the double segmentation should stop the re-ignition of discharges.

A GE1/1 detector was assembled with a stack of three doubly segmented GEM foils. The detector was then operated at $G_{\text{eff}} = 10^4$. The discharge propagation probability was measured to be $\leq 4\%$ with confidence level of 68%. No damage at all were observed and all the discharge events observed looked like the one shown on Fig. 4.38a. Additionally the discharge propagation probability was measured as a function of the induction field, and it matched the $10 \times 10 \text{ cm}^2$ trend (see Fig. 4.38b).

The doubly segmented foil is at the moment the best solution for the discharge mitigation and it is also a very promising solution for the future GE2/1 and ME0

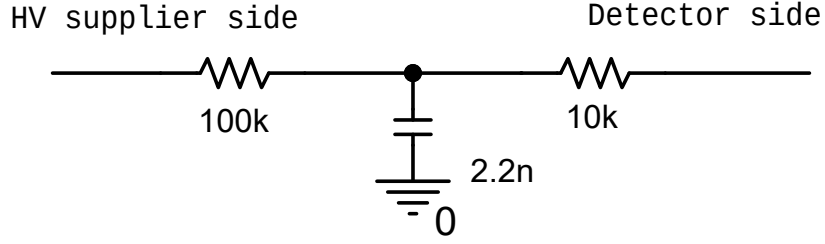


Figure 4.39: Original GE1/1 HV filter scheme

detectors. Further measurements have to be performed to fully characterized this new design.

4.5 Final implementation

The lessons learned from the tests detailed in the previous sections, allowed our group to propose an improvement in the GE1/1 detector design able to mitigate the discharge and also the eventual damages on the front-end electronics. The final implementation proposed includes

- the increase of the HV filter resistor;
- $470\ \Omega$ resistors in the hybrid version 3 boards.

The measurements detailed in the previous section, shows a drastic reduction in damage probability with the hybrid v3 $470\ \Omega$ and the change in the HV filter swapping the resistors from $10\ \text{k}\Omega$ to either $100\ \text{k}\Omega$ or $1\ \text{M}\Omega$. These changes need to be effectively tested before being implemented in the GE1/1 upgrade project.

The greater is the impedance of the resistors inside the HV filter, the greater will be the voltage drop, at a given fixed current drawn. For instance with the $10\ \text{k}\Omega$ HV filter (see Fig. 4.39), $1\ \mu\text{A}$ of current drawn on the n -th channel, would lead to a voltage drop of $0.11\ \text{V}$, while with $1\ \text{M}\Omega$ it would be $1.1\ \text{V}$. The voltage drop will be negligible if the resistance value is much less than $100\ \text{k}\Omega$.

An high rate of particle crossing the detector releases a large amount of primary electrons that will be amplified and lead to a significant current draw, affecting the detector performances as shown before. For this reason a rate capability measurement was performed.

4.5.1 Rate capability comparison

In order to chose the most suitable decoupling resistors for the HV filter, we compared the rate capability of the original $10\ \text{k}\Omega$, the $100\ \text{k}\Omega$ and the $1\ \text{M}\Omega$ HV

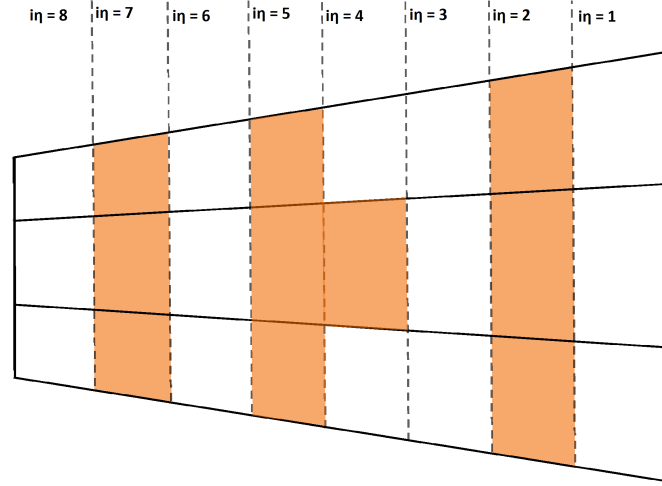


Figure 4.40: The sectors of the GE1/1 detector that are involved in the rate capability measurements have been highlighted.

filter resistors. This comparison consists in the measurements of the anode current density while increasing the rate of incoming particles, in order to check what is the range in which the detector amplification is independent from the hit rate. The HV filters under test are:

- 10 k Ω (default filter): each GEM foil electrode is powered through the HV filter circuit shown on Fig. 4.39;
- 100 k Ω : each GEM foil electrode is powered through a variant of the default HV filter, in which all the 10 k Ω resistors are replaced with 100 k Ω resistors;
- 1 M Ω : each GEM foil electrode is powered through a variant of the default HV filter, in which all the 10 k Ω resistors are replaced with 1 M Ω resistors.

The measurement was carried out by using the same detector instrumented with one of the HV filters mentioned above. The detector was installed in the X-ray box, in a fixed position throughout the whole measurement, and powered at $G_{\text{eff}} = 1.8 \times 10^4$, while the anode current was independently read from 4 different readout sectors (see Fig 4.40). In order to disentangle the differences in the readout sector surfaces, all the anode current data will be referred to the unit area. The power supplied to the X-ray gun was stepwise increased in order to increase the hit rate on the detector. We can assume that the produced hit rate on the detector due to the X-Ray source is proportional to the power at which the X-ray is fed. In this way, we can compare the rate capability of each configuration by comparing the trend of the anode current density versus the power of the X-ray gun. Fig. 4.41 summarizes this measurement with a plot for each of the 4 sectors under test. In each plot, the first five points of the 10 k Ω dataset, have been with a straight line that is

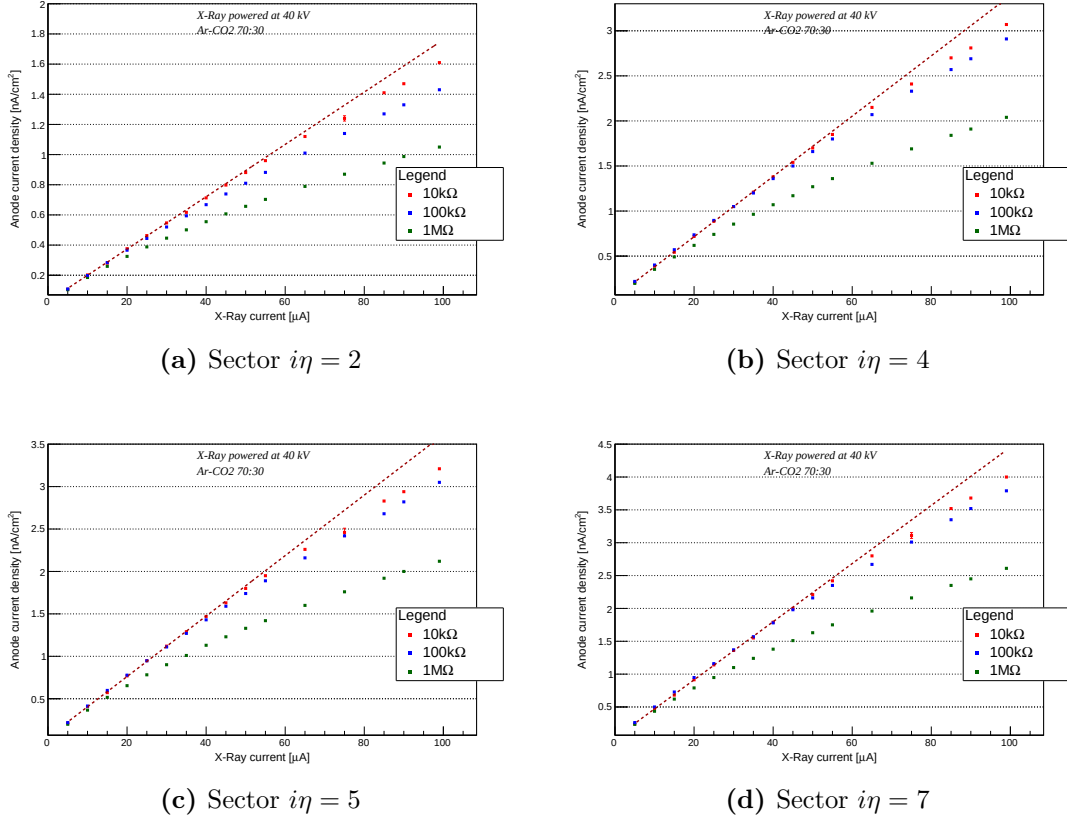


Figure 4.41: Comparison between the rate capability of the HV filters under test. On the y-axis is shown the anode current density while on the x-axis the current that fed the X-ray gun [61].

drawn in red over the whole x-axis. As the HV filter is changed, all the other measurement conditions remain the same, therefore it is reasonable to expect that the anode density current does not vary to much, unless the rate capability of the configuration is exceeded. The differences in the anode density current between the $i\eta$ sectors, can be ascribed to a variation of the incoming particle fluxes. As can be seen, in case of the 1 MΩ configuration, the linearity between the X-ray current and the anode current density is lost much earlier with respect to the 100 kΩ, while they have similar performance when it comes to the front-end damage probability.

For the final GE1/1 installation an implementation with a 200 kΩ has been chosen, because it grants the decoupling performance needed to stop the discharge re-ignition while still ensuring a rate capability comparable with the one from of the original design.

4.5.2 Conclusion

The R&D campaign named GEM Sustained Operations was concluded with the great achievement of an implementation that grants, at the same time, the mitigation of the discharges and a more protected front-end electronics. The damage probability of the front-end electronics was indeed lowered from the initial $\geq 90\%$ of the initial configuration, to the $\leq 4\%$ of the final design. Furthermore the final implementation of the GE1/1 detectors has been proven to have a rate capability comparable with the one of the original design. Finally the technical time needed to perform all the suggested improvements that, does not affect the scheduled installation window that is open in the biennium 2019/2020.

Apart for the direct results on GE1/1 detectors mentioned above, the many tests performed allowed us to:

- find the origin of the worrying channel loss observed in the Slice Test;
- measure the damage and the discharge probability for different configurations;
- better understand the propagation process, and under which conditions it may lead to channel loss;
- highlights the differences in the discharge evolutions between the $10 \times 10 \text{ cm}^2$ prototype and a large detector;
- propose a new design for the GEM foil that has been proved to be a valid solution for the upcoming GE2/1 and ME0.

CHAPTER 5

Conclusions

The upgrade of the CMS muon system foresees the installation of triple-GEM detectors in the forward η station GE1/1. The GE1/1 detectors will be installed during the LS2 and have to provide reliable tracking and triggering performance for about one decade in the CMS experiment. The Gas Electron Multiplier (GEM) is a new detection technology in the CMS experiment, therefore an operational test was conducted during 2017-2018, with a total number of 5 installed detectors. An irreversible front-end channel loss has been observed during the two years of operational test. The work presented in this thesis describes the contribution I gave to address this problem.

A GE1/1 detector set-up was instrumented in the laboratory and four different hypothesis were tested as the cause of channel loss: the LV failure, the normal operation, the ^{109}Cd irradiated operation, and discharges that propagates to the anode plate. After 80 days of test, the results showed that the hypothesis of LV failure, normal operation and ^{109}Cd irradiated operation could be ruled out. The only mechanism that could lead to channel loss was ascribed to the discharges that reach the anode plate. This evidence suggested to improve the front-end channel spark protection, by designing two new hybrid plugin boards for the ASIC. On the other hand the discharge probability and the propagation probability were measured for a GE1/1 detector.

The discharge hardness of the new hybrid designs has been tested, by measuring the damage probability. Additionally, by studying the development of discharges that propagate to the anode plate, the phenomenon of discharge propagation re-ignition has been observed and it has been correlated with an increased damage probability. By increasing the decoupling resistors in the detector HV filter, the discharge propagation re-ignitions have been stopped. An important result was achieved: the front-end damage probability was reduced from the initial 92% to the $\leq 4\%$ of the final implementation, without affecting the schedule of the GE1/1 installation.

Finally a new design for the GEM foil was proposed, based on the observations

that arose during the tests. The innovation consists in the segmentation of the bottom GEM electrode in order to limit the amount of charge that can flow during a discharge. A GE1/1 detector has been instrumented with the new GEM foil design, and the measurements performed have shown that the phenomenon of discharge propagation toward the anode plate does not take place. Further measurements are needed to fully characterize this new foil design and to confirm that it is the most suitable design for the triple-GEM detectors that will be installed in the GE2/1 and ME0 stations of the CMS muon system during the Long Shutdown 3 (LS3).

Acronyms

ASIC	Application Specific Integrated Circuit	37
ATLAS	A Toroidal LHC Apparatus.....	3
BX	Bunch Crossing.....	10
CDF	Cumulative Distribution Function.....	47
CERN	European Organization for Nuclear Research	1
CFD	Constant Fraction Discriminator	41
CMS	Compact Muon Solenoid	3
CP	Charge-Parity.....	4
CSC	Chatode Strip Chamber.....	7
DAC	Digital to Analog Converter	43
DAQ	Data Acquisition.....	41
DM	Dark Matter	4
DT	Drift Tube.....	6
EM	Electromagnetic	6
ENC	Equivalent Noise Charge.....	43
ESD	ElectroStatic Diode	41
EW	ElectroWeak	2
EWSB	ElectroWeak Symmetry Breaking	3
GEB	GEM Electronics Board.....	41
GEM	Gas Electron Multiplier	ii
HEP	High Energy Physics.....	15
HIP	Highly Ionizing Particle.....	13
HL-LHC	High Luminosity LHC	ii
HLT	High Level Trigger.....	8
HV	High Voltage	44

IP	Interaction Point.....	5
L1	Level 1	8
LHC	Large Hardon Collider	ii
LHCb	Large Hadron Collider beauty.....	21
LS2	Long Shutdown 2.....	ii
LS3	Long Shutdown 3.....	8
Micromegas	Micro Mesh Gaseous Structure.....	18
MPGD	Micro Pattern Gaseous Detector.....	15
MSGC	Micro-Strip Gas Chamber.....	18
MWPC	Multiwire Proportional Chamber.....	17
OH	OptoHybrid.....	41
PFA	Prompt Feedback Analysis.....	38
PU	Pile Up.....	10
QC	Quality Control.....	57
QCD	Quantum Chromodynamics	2
RPC	Resistive Plate Chamber	6
SM	Standard Model.....	1
SNR	Signal to Noise Ratio	41
TOTEM	Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC.....	21
WIMP	Weakly Interactive Massive Particle.....	4
YETS	Year-End Technical Stop.....	9

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