



UNIVERSITÀ
DEGLI STUDI DI BARI
ALDO MORO

UNIVERSITÀ DEGLI STUDI DI BARI “ALDO MORO”
Dipartimento interateneo di Fisica “Michelangelo Merlin”

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Performance of micro-pattern gaseous detectors at the LHC and future collider experiments

Dottorando:

Antonello Pellecchia

Supervisor:

Dr. Piet Omer J. Verwilligen

Prof. Anna Colaleo

Coordinatore:

Prof. Giuseppe Gonnella

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Chapter 1

Introduction

The Standard Model of particle physics and its experimental confirmation are among the great scientific achievements of the late 20th and the early 21st century. The discovery of the Higgs boson [1] at the Large Hadron Collider [2] (LHC) has marked the beginning of a new season of verifications of the Standard Model and searches for its extension. In this framework, the upgrade of the LHC experiments for the High-Luminosity LHC phase highlights the role played by the progress of scientific instrumentation in the progress of physics.

In the LHC Phase-2, the LHC experiments need to maintain the same performance achieved in the last ten years while sustaining higher luminosity and pile-up; the new detectors need to sustain higher rates and reach better space and time resolutions while ensuring affordable mass production to cover large areas. This trend can be only seen as increasing with future high-energy physics experiments that will follow after the end of the HL-LHC.

This thesis research is focused in the development of micro-pattern gaseous detectors (MPGDs) for high rates and time resolutions for the Compact Muon Solenoid [3] (CMS) experiment at the LHC and for future colliders; the context for the MPGD development in perspective for the physics at the HL-LHC and future colliders, together with the outline of the thesis content, are sketched in the next sections.

LHC motivations

The Standard Model of particle physics is a Yang-Mills theory [4] built on the group $SU(3) \otimes SU(2) \otimes U(1)$ that describes the dynamics of the fermions and the strong and electroweak fundamental interactions. A key aspect of the Standard Model is the electroweak symmetry breaking, a mechanism that gives mass to the $W^\pm$ and Z^0 bosons and prescribes the existence of a scalar particle, the Higgs boson.

One run of the LHC has passed since the first observation of the Higgs boson by the ATLAS [5] (A Toroidal LHC Apparatus) and CMS experiments. Higgs boson properties such as spin-parity ($J^{CP} = 0^{++}$) and width have been measured; the couplings of the Higgs boson with the W and Z bosons have been measured with $\sim 10\%$ precision, as well as those with the third-generation fermions (the t and b quark and the τ lepton), while evidence of $H \rightarrow \mu\mu$ decay has also been found at the level of 3σ significance. In all cases the relation between the

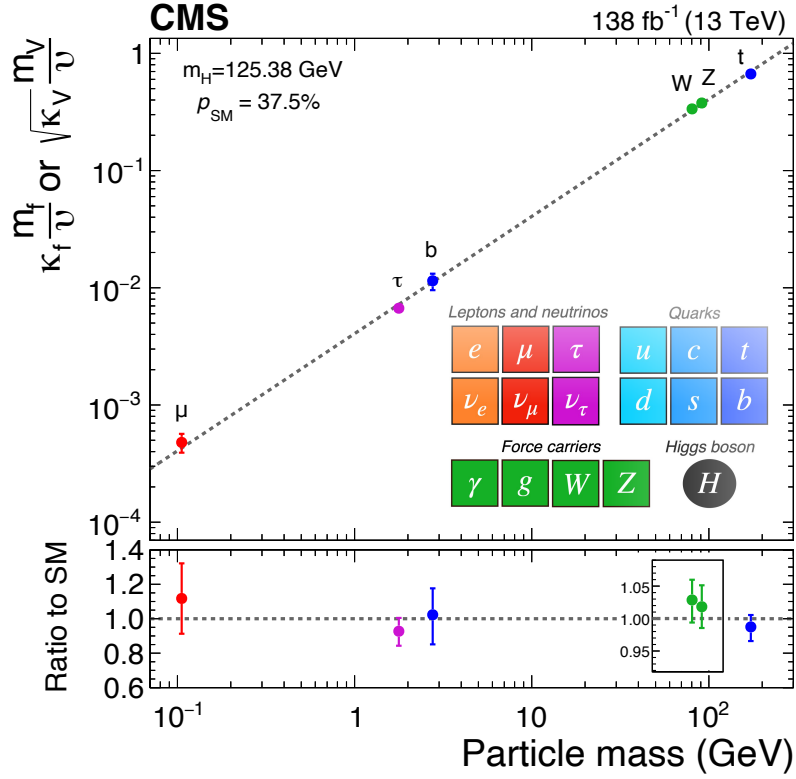


Figure 1.1: Coupling of the Higgs boson with the Standard Model particles measured at the CMS experiments as a function of the particle masses [6].

particle masses and their coupling to the Higgs boson (Fig. 1.1) has been in agreement with the Standard Model prediction.

On one hand, the outstanding agreement of the LHC experimental findings with SM prediction still needs to be tested with the Higgs boson coupling to lighter fermions (the electron and the s and c quarks) and with $O(1\%)$ precision measurements on the heavier particles. Multi-Higgs production – needed to determine its self-interaction terms – has not yet been observed. On the other hand, several instances of possible beyond-Standard Model (BSM) physics can be probed in the Higgs sector, through processes such as invisible or lepton-flavour violating decays; such observations might be evidence of dark matter production, multi- or composite-Higgs theories or extra-dimensional models.

More broadly, an extension to the Standard Model will eventually be needed to explain essential open questions in physics, such as the naturalness and the mass hierarchy problem.

High-Luminosity LHC and future colliders

These motivations justify an extension of the LHC with an increased luminosity – as well as increased energy –, to collect a statistics nine times higher than in the first three LHC runs. Further down the road, future colliders such as the proposed Future Circular Collider [7] (FCC) and the Muon Collider [8] would allow precision measurements not feasible at the HL-LHC, such as multi-Higgs coupling and Higgs boson coupling to first-generation fermions. Both the HL-LHC and future colliders will deliver higher center-of-mass energies and unprecedented luminosities; future experiments, as well as the upgrades of existing experiments, require particle detectors able to cope with high background rates, while providing good space and time resolutions to ensure strong pile-up mitigations and high longevity to ensure reliable physics data taking for decades.

The HL-LHC will deliver a maximum instantaneous luminosity ranging from 5 up to ultimately $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$; the ongoing upgrades of the LHC experiments are aimed at maintaining low momentum thresholds while keeping the trigger rates of the first three LHC runs, coping with pile-up between 140 and 200 and in some cases extend the geometrical acceptance of the detectors.

The main LHC experiment in the focus of this thesis is the CMS, and in particular the Phase-2 upgrade of its muon spectrometer with the addition of two new stations based on GEM detectors. GEM detectors belong to the class of micro-pattern gaseous detectors, a technology born in the late 1980s – with the conception of the micro-strip gas chamber (MSGC) by Anton Oed [18] – that found several applications for tracking and triggering in major particle physics experiments. The second main focus of this thesis is the development of a micro-pattern gaseous detector for fast timing (FTM) for application in high-rate environments in future experiments.

Thesis outline

The first chapter of this thesis discusses the basic working principles of MPGDs and provides examples of their application in HEP experiments; the GEM upgrade is framed in the context of the CMS experiment and a background is given on the history of the three CMS GEM stations, its baseline design and the installation and commissioning of GE1/1, the first CMS GEM station.

The second chapter presents the performance of the triple-GEM detectors for the GE2/1 and ME0 stations of the CMS upgrade as measured in 2021 and 2022 in two test beam campaigns. The detector requirements and specifications are first described together with the test beam setup and the data acquisition (DAQ) software. My activity for the GEM test beam has been the integration of the GE2/1 and ME0 electronics to ensure good data taking conditions, the calibration and commissioning of the test beam detector and electronics, the monitoring of its data taking and the development of an offline reconstruction and analysis framework for the test beam data.

The third chapter summarizes the high-rate studies performed for the ME0 station of the CMS muon spectrometer; after a renewed campaign of rate capability tests with irradiation

on GEM detectors over large areas, the ME0 detector optimization for high-rate is introduced. The studies close up with a measurement of the rate capability of the new detector design with final electronics at a test beam and an evaluation of the ME0 performance in the HL-LHC expected background environment.

When I joined the activity on the high-rate studies for ME0, I worked on analyzing the first detector data of the ME0 rate capability measurements in the laboratory with x-rays; I compared the CMS background simulations with the results of the rate capability measurements and determined possible improved detector layouts to mitigate the expected ME0 gain loss. After a new possible solution consisting of a new layout for the detector segmentation was identified, I determined the optimal segmentation layout for the minimization of the gain loss and participated to the validation of prototypes with the new design. Finally I demonstrated the operation of the ME0 detector with final electronics in a test beam at the GIF++, showing the impact of the electronics dead time on the ME0 efficiency.

The fourth chapter describes the recent developments towards a fast timing MPGD (FTM), a detector designed for a sub-ns time resolution; the history of the FTM prototypes is shown together with the set of goals needed for the proof of its working principle. I worked on designing a laser setup for the characterization of a new FTM prototype and I compared the performance of different detector layouts and gas mixtures, trying to improve its gain and signal efficiency. I chose and tested different fast-timing detectors and evaluated them as a time-tagger for the FTM. Finally, I identified the technical advancements needed for overcoming the limitations in the present FTM performances.

Chapter 2

Micro-pattern gaseous detectors at collider experiments

The rise of micro-pattern gaseous detectors (MPGDs) fulfils an increasing demand of particle detectors for high rates over large areas in high energy physics experiments.

The present chapter summarizes the general working principles of MPGDs and the most consolidated MPGD technologies that have been chosen for present-generation experiments; a more in-depth explanation is dedicated to GEM detectors and their use in the CMS experiment, one of the main scopes of application of the work discussed in this thesis. The topics are treated by emphasizing the tools used in the next chapters.

2.1 Physics of micro-pattern gaseous detectors

2.1.1 Working principles and performance of gaseous particle detectors

The three essential steps in the physical understanding of gaseous particle detectors are the primary ionization, the charge drift and multiplication and the signal induction and readout.

Primary ionization. Most micro-pattern gaseous detectors base their principle on the amplification of a primary charge released in the gas by a passing particle. For a high-energy charged particle, the average energy loss through a medium per unit length due to electromagnetic processes depends of the $\beta\gamma$ of the particle and is well described by the Bethe-Bloch equation [9]; the statistics of the energy loss follows a Landau distribution around the average [10]:

$$f(\lambda) = \frac{1}{\sqrt{2\pi}} e^{\frac{1}{2}(\lambda + e\lambda)}, \text{ with } \lambda = \frac{\delta E - \delta E_{\text{MP}}}{\xi}, \quad \xi = K \frac{Z}{A} \frac{\rho}{\beta^2} x,$$

due to the high-energy tails dominated by rare delta electron emission. For a minimum-ionizing particle, the average energy loss is approximately independent of the medium characteristics other than its density and is approximately $2 \text{ MeVcm}^2/\text{g}$; for a MIP passing in a

mixture of Ar and CO₂ with 70% and 30% mass fractions (density $1.81 \times 10^{-3} \text{ g/cm}^3$) it is 3.62 keV cm^{-1} .

The energy loss is not continuous through the medium, but distributed in clusters. For example, the average number of clusters per unit length generated by a MIP in Ar:CO₂ 70%:30% is 29 cm^{-1} [11]. Since the largest part of the energy loss for a MIP happens by ionization – while radiative processes dominate only at higher energies – this results in the production of 29 primary electron-ion pairs per cm. The distribution of the production positions of the cluster is poissonian: this allows calculating the maximum theoretical efficiency of a gaseous detector – assuming the primary ionization happens in the gas – as the probability of having at least one cluster produced in the drift gap. If d is the drift gap thickness and λ is the average number of clusters per unit length, the efficiency is

$$\epsilon = 1 - P(0) = 1 - e^{-\lambda d},$$

for a MIP in a detector with a primary ionization volume of 3 mm thickness filled with Ar:CO₂ 70:30, the maximum efficiency is 99.99%.

There is no analytic formula to calculate the number of ionization clusters by a charged particle; however, the primary electron-ion pairs released in a medium typically thermalize very fast, releasing a higher number of secondary pairs from collisions. At first order – neglecting processes such as recombination or Penning transfer – the total number of secondary electron-ion pairs can be calculated from the energy loss as $n_T = \delta E/W$, where W is the average ionization energy of the medium; in case of a mixture it is equal to the average of the ionization energies of each component weighted by its mass fraction. For Ar:CO₂ 70:30 ($W = 27.2 \text{ eV}$) the average number of secondary electron-ion pairs in 3 mm of gas gap is

$$n_T = \frac{dE/dx}{W} d = \frac{3.62 \text{ keV/cm} \times 0.3 \text{ cm}}{27.2 \text{ eV}} = 39.9. \quad (2.1)$$

Differently from charged particles, photons below 100 keV typically interact destructively with matter; the evolution of a photon beam through a thin layer of material is described by the Lambert-Beer law [12]. The energy threshold for single-photon interaction is in the far ultra-violet in most gas mixtures, while multi-photon interaction (see chapter 5) allows ionization in the blue and UV regions.

For soft x-rays, the dominant interaction process is photoelectric effect; Eq. 2.1 still holds, but the entire energy of the photon is released; for example, the average number of secondary electrons released in Ar:CO₂ 70:30 by an 8 keV photon is 294. The statistics of the number of electrons released is not poissonian, since the energy loss is constrained to be at most equal to the energy of the photon: the variance of the distribution of n_T is limited to $\sqrt{F n_T}$ by the Fano factor $F < 1$ [13].

Drift and avalanche formation. In absence of electric fields in the gas, the primary electrons and ions from a ionization event rapidly thermalize and recombine. When low electric fields are applied with external electrodes, the average motion of the electron and ion clouds are both uniform, with drift velocities proportional to the electric field itself; the proportionality constant $\mu^\pm$ is called ion (or electron) mobility. Typical values for the drift

velocity of ions in low fields are of the order of 1×10^5 cm/s for most detector mixtures, while for electrons they are two orders of magnitude higher due to their lower mass; the motion is well described by a drift-diffusion equation, with diffusion coefficients proportional to the drift velocity of the two species (Nernst-Townsend formula [14]):

$$\frac{D}{\mu} = \frac{k_B T}{e}.$$

While the ion mobility stays approximately constant at electric fields above 10 kV/cm, the motion of an electron changes when its energy overcomes the ionization potential of the gas atom or molecules; the gas ionization by the electrons releases other electrons, which in turn can ionize the medium, developing an avalanche. The avalanche size is determined by the first Townsend coefficient α , equal to the average number of electrons released by unit length dN/dx .

The avalanche stops when all the electrons have been collected at the anodes. In absence of secondary emission of other particles such as UV photons, the total produced charge is proportional to the primary charge and the multiplication factor is $M = \exp \int_{x_0}^x dx \alpha(x)$; in such conditions, the detector is said to work in proportional regime. No universal parameterization exists for the first Townsend coefficient, which has to be measured for each mixture, but in fields of the order of tens of kV/cm it is observed to be approximately proportional to the electric field magnitude; therefore, in detectors in which the avalanche multiplication happens in regions with approximately constant electric fields the amplification is exponential in the field.

The statistics of the avalanche multiplication for a single primary electron depends on the intensity of the electric field [11]. At low fields, the average energy of an avalanche electron is low enough to assume that its secondary electron – created by ionization – is produced with low kinetic energy; each multiplication step is therefore independent on the previous one and the distribution of the number of electrons in the avalanche is exponential (Yule-Furry law). This single-electron energy spectrum is observed in MPGDs such as GEM detectors that are operated at gains of the order of 10^4 .

At high electric fields, the energy of an electron between two gas collisions may be large enough to produce secondary electrons with high initial kinetic energy, that need to travel a reduced path before ionizing the gas themselves; the collisions in the avalanche are no more independent and the avalanche spectrum is described by a Polya distribution. While an exponential distribution is monotonically decreasing, the Polya single-electron spectrum has a most probable value $N_{\text{MPV}} > 0$; its variance $\sigma_N^2 = \bar{N}/(\theta + 1)$ is also reduced with respect to the exponential by a parameter $\theta > 0$ that depends on the gas mixture and electric field.

The avalanche created by n_T primary electrons is simply the sum of n_T independent avalanches; using the central limit theorem, the avalanche statistics becomes closer to a gaussian as n_T increases – although with large non-gaussian tails.

There is no theoretical limit to the avalanche size; in practice, the maximum reachable amplification is set by the streamer probability due to UV photons that originate from recombinations in the avalanche: this photons can begin secondary avalanches by ionizing other gas molecules or hitting the electrodes, a process that can go on in cascade eventually causing a spark breakdown. An experimental bound to the avalanche size before a breakdown occurs is

Raether’s limit of 10^7 total electrons [15]; for a detector with ten to 100 primary electrons per event, this limit sets the maximum reachable amplification to 10^5 , while the practical average value is lower due to the large variance of the avalanche statistics¹.

Signal induction. The moving charges in the avalanche induce a charge on all the electrodes of the detector, including the readout element; the evolution of the avalanche over time determines a current signal on the readout that is further processed by the front-end electronics.

In a detector made only of conductive materials, the signal induced on a readout electrode by a moving charge is determined by the weighting field $\mathbf{E}_w$. The weighting field is calculated in a geometry in which the voltage of the readout electrode is set to an arbitrary value V_0 , all the other electrodes are grounded and the moving charge is removed; once $\mathbf{E}_w$ is known, the signal induced by a single point charge q is determined by the Ramo-Shockley theorem [16, 17]:

$$i(t) = \frac{q}{V_0} \mathbf{E}_w \cdot \mathbf{v}(t), \quad (2.2)$$

where $\mathbf{v}$ is the velocity vector of the charge.

The current signal induced by an avalanche is the sum of the currents of the single charges in the avalanche; the signal ends when all the charge is collected.

2.1.2 Micro-pattern gaseous detectors

The class of micro-pattern gaseous detectors (MPGDs) includes all gaseous detectors containing amplification structures of sub-millimeter size manufactured through photolithography techniques.

Historically, MPGDs were born in the late 1980s from the need to overcome the limit of space resolution and rate capability of consolidated detector technologies such as multi-wire proportional chambers (MWPC); most of the issues in the operation of MWPCs at high-luminosity experiments would come from the difficult manufacturing, which made detectors of small wire pitch sensitive to damage or mechanical stress, or from the slow signal formation times, which made its performance affected by the ion space charge. The detector considered the first historical example of MPGD, the micro-strip gas chamber [18] (MSGC), already contained all the common characteristics shared by other MPGD technologies. A MSGC is made of a gas volume delimited by a drift electrode on top and an insulating plane at the bottom (Fig. 2.1); the dielectric was coated with thin parallel metal strips, of width between 10 and 100 μm and pitches of the order of a few hundred μm , alternatively biased with negative voltage to collect ions (cathode) or grounded to collect electrons and for signal readout (anode). The charge multiplication was ensured by the intense electric field close to the strips.

Common features of the MSGC – at least in its “bare” design – that can be identified even in present generation MPGD are:

¹This limit is even lower for micro-pattern gaseous detectors with a single multiplication stage, in which imperfections in the amplification structures might result in locally high fields; this issue in modern MPGDs is partially mitigated by the use resistive electrodes.

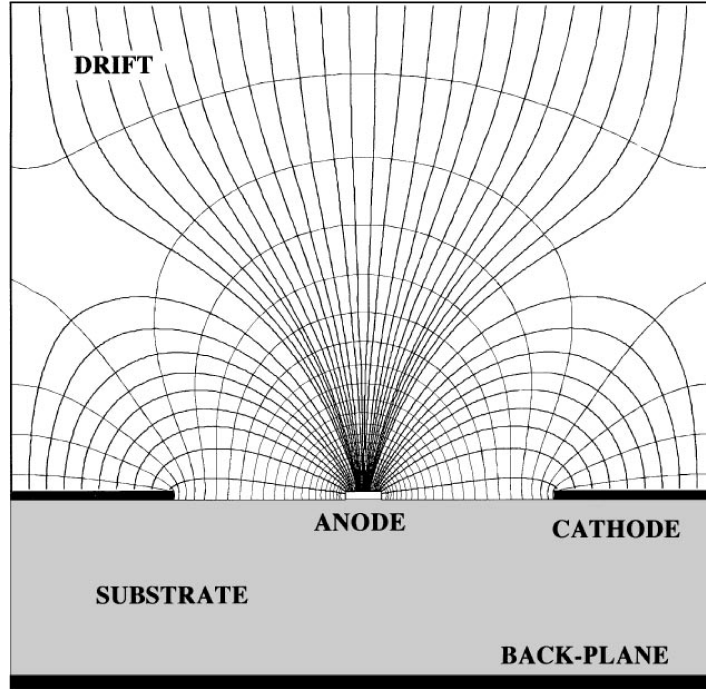


Figure 2.1: Electric field and equipotential lines in a micro-strip gas chamber [18].

- a well-defined separation between a drift region, where the primary ionization occurs, and a thinner multiplication region;
- stable operation restricted to the proportional mode with low gains, of the order of 10^4 (lower than the 10^6 gains reachable with other gaseous detector technologies);
- a good space resolution, of the order of $100\text{ }\mu\text{m}$, due to the small pitch of readout elements and the small spreading of the charge avalanche as a consequence of the low gain;
- a time resolution of the order of few ns, dominated by the fluctuations in the position where the first cluster to reach the amplification region is created;
- an excellent rate capability up to fluxes of few MHz/mm^2 , thanks to the short distance (hundreds of μm) between cathode and anode that ensure short collection times (within a few μs) of the slow ions.

One prominent flaw in the MSGC concept was the high sensitivity to discharges, resulting in damages such as short circuits between electrodes or destruction of the electrodes themselves, that prevented its operation in nominal conditions; the particular attention to discharge damage and its mitigation has been a connecting line driving the development of several subsequent MPGD technologies. Some of these mitigation techniques are common across different classes of detectors:

- geometries with flat equipotential surfaces in the amplification region, to lower the charge density (MicroMegas);
- cascading multiple amplification stages (GEM);
- embedding resistive materials (MicroMegas, μ -RWELL, resistive GEM).

2.1.3 Gaseous detectors with resistive electrodes

Several emerging gaseous detector technologies include resistive elements. However, the first resistive gaseous detectors, Iarocci tubes [19], date back to the 1970s; other resistive detectors invented soon after, such as resistive plate chambers [20] (RPC), still enjoy widespread use across major high-energy physics experiments.

RPCs are parallel plate counters in which at least one electrode is made of a material with high resistivity – of the order of $10^{10} \text{M}\Omega \cdot \text{m}$ – such as glass or bakelite; the main advantage over traditional plane counters was increased spark protection, as in presence of high currents the resistive layers exhibit a voltage drop that can quench discharges.

The rise of resistive materials for other gaseous detectors, especially in MPGDs, is a result of the recent improvement of the coating technologies of thin resistive layers and of the etching of laminates including resistive layers; since MPGDs are particularly sensitive to discharge damage due to the presence of small structures, one of the most attractive features of resistive materials in MPGDs is, as for RPCs, the improved spark protection.

A second advantage of resistive materials in gaseous detectors is the possible improvement of tracking precision. The typical space resolution of MPGDs is better than traditional gaseous detectors: this is in part thanks to their operation in proportional mode and in low gain, which reduces the avalanche spreading if compared, for example, to RPCs; moreover, the manufacturing of readout planes with high granularity (e.g. PCBs with strips or pads) is typically simpler and easier to automate for MPGDs than detectors such as multi-wire proportional counters, which use wires as readout elements. For a detector with a plane of anodic strips read out by digital front-end electronics, the expected space resolution is strip pitch/ $\sqrt{12}$; if the readout plane is covered by a thin layer of resistive material, the charge collected by the resistive layer spreads out while diffusing towards the readout strips. The charge density follows the telegraph equation (with R the surface resistivity of the material and C its capacitance per unit area) [21]:

$$\frac{\partial \rho}{\partial t} = \frac{1}{RC} \nabla^2 \rho, \quad (2.3)$$

i.e. a delta-shaped charge spreads out as a gaussian cloud with time constant per unit area RC . This behaviour can be used to maintain a limited granularity of readout strips while recovering good space resolution: if the front-end electronics features charge readout, the position of the charge spreaded out over several strips can be recovered with good precision by a center-of-gravity calculation.

A third effect arising in presence of resistive elements is transparency: while a conductive electrode shields the external conductors from the charge flowing inside the detector, using only resistive electrodes allows inducing on a single layer of strips the signals generated by several detector layers. The principle is at the basis of multi-gap RPCs (MRPCs), which are

made of several resistive layers of reduced gas gap; the readout signal is the sum of the signals induced by each layer, so its arrival time is the average between the arrival times of each layer: for a detector with N gaps, the time resolution is in theory improved by a factor of $1/\sqrt{N}$, while the presence of multiple layers ensures that even with gap thicknesses of a few hundreds of μm the efficiency is still close to 1 [22]. The success of MRPCs is then ensured by their good time resolution, down to below 100 ps, achievable with a relatively simple structure [23].

Finally, in resistive detectors, the theory of signal induction has to be modified because Green's reciprocity theorem, on which the Ramo-Shockley formula is based, does not hold in presence of resistive materials. The generalized formulation of the signal induction theory is based on the electrostatics of weakly conductive media: the Poisson equation, written in the Laplace domain, is [24]

$$\nabla \cdot (\epsilon'(\mathbf{x}, s) \nabla \bar{\phi}(\mathbf{x}, s)) = -\frac{\bar{\rho}(\mathbf{x}, s)}{\epsilon_0}, \quad (2.4)$$

where $\bar{\phi}$ and $\bar{\rho}$ are the Laplace transforms in the time variable of the electrostatic potential and of the electrostatic charge density: the dielectric constant ϵ of each medium is replaced by the “effective” dielectric constant

$$\epsilon'(\mathbf{x}, s) = \epsilon(\mathbf{x}) + \frac{\sigma}{\epsilon_0 s}. \quad (2.5)$$

The weighting field for a readout electrode is replaced by a time-dependent weighting field $\mathbf{E}_w(\mathbf{x}, t)$ that is obtained in the Laplace domain by removing all the free charges, grounding all the electrodes while applying an arbitrary fixed voltage V_0 to the readout electrode and solving the Poisson equation 2.5; this is equivalent to solving the Poisson equation in the time domain (with effective dielectric constant ϵ') with a delta voltage pulse $V_0\delta(t)$ on the readout electrode. The generalized Ramo-Shockley theorem states that the induced current by a moving point charge q is

$$i(t) = \frac{q}{V_0} \int_0^t dt' \mathbf{E}_w(\mathbf{x}, t - t') \cdot \mathbf{v}(t). \quad (2.6)$$

2.2 MPGD technologies and applications

2.2.1 MicroMegs

A Micro-Mesh Gaseous Structure [25] (MicroMegs) is an MPGD in which the amplification region is delimited by a thin metallic mesh on top and an anode plane at the bottom; the drift region is defined by an electrode placed above the mesh (Fig. 2.2a). Typical thicknesses are of the order of 100 μm for the amplification region and 3 to 6 mm for the drift gap; the mesh thickness is typically between 5 and 20 μm , with pitches of about 60 μm .

The amplification field lines resemble those of a thin gap parallel counter; thanks to the spatial uniformity of the avalanche, the energy resolution is very small (a FWHM of 5% for 22 keV x-rays was observed). Gains of $10^4 - 10^5$, depending on the primary charge, can be reached with stable operation. With optimization of the ratio between the drift and the amplification electric fields, the transparency of the mesh to primary electrons can be

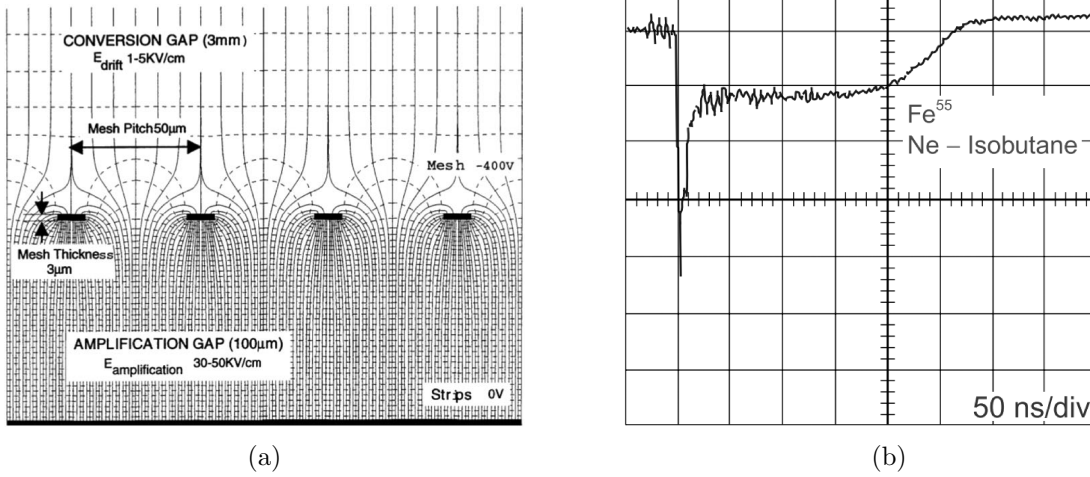


Figure 2.2: (a) Electric field lines and equipotential lines in a MicroMegas [26]. (b) Readout signal of a MicroMegas acquired with a current preamplifier [27].

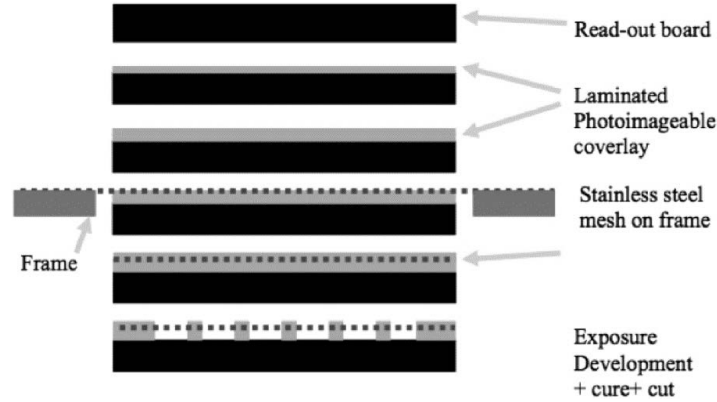


Figure 2.3: Production scheme of a bulk MicroMegas [28].

maximized; at the same time, the transparency of the mesh to avalanche ions has to be minimized to avoid rate capability effects due to the ion backflow. The typical shape of a MicroMegas signal, as shown in Fig. 2.2b, has a fast electron peak of a few ns rising edge followed by a slow ion tail.

The manufacturing of MicroMegas has been optimized over the years for a simple assembly over large areas: the most consolidated process is the “bulk” MicroMegas scheme (Fig. 2.3), in which the mesh is manufactured commercially and embedded in the photoresist layer [28]. The etching then removes the insulator leaving the amplification gap exposed, except for pillars of millimetric size which ensure the mesh planarity.

An essential aspect in the MicroMegas design optimization has been the protection against discharge damage: high discharge rates are observable at large gains in high-rate beams, presumably due to highly-ionizing particles that overcome the Raether limit. One among the main mitigation strategies consists of coating the anode with resistive strips or pads (Fig. 2.4),

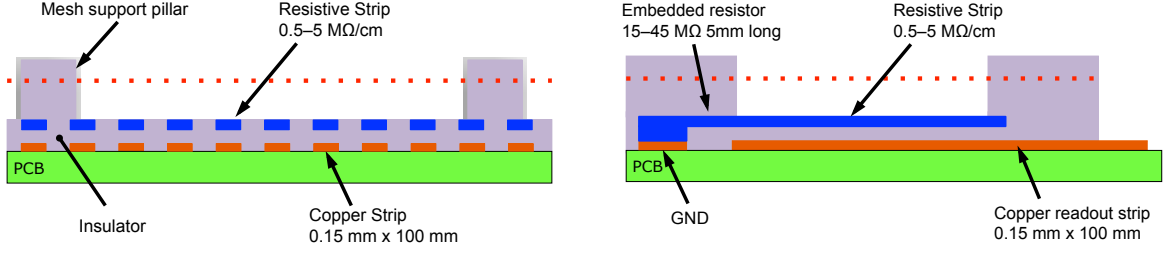


Figure 2.4: Layout of a resistive MicroMegas [29].

which are separated through an insulator from the underlying copper readout plane; the latter receives the signal by pick-up from the resistive anode and is connected to the front-end.

Resistive MicroMegas have shown excellent stability at gains of the order of 10^4 in mixtures such as $\text{Ar}:\text{CO}_2:\text{C}_4\text{H}_{10}$ 93:5:2; on the other hand, the resistive layout introduces a limitation of the rate capability, with observable gain drops at rates of tens of kHz/cm^2 . Several improved layouts of resistive MicroMegas have been designed and tested over the years, some including multiple resistive layers connected through copper vias to the readout plane; the vias provide charge evacuation lines and limit gain losses at high rates due to local voltage drops under irradiation [30]. Prototypes with small-pad readout planes (of few mm pitch) have been shown to maintain high efficiency under intense irradiation thanks to the high readout granularity.

The ATLAS New Small Wheel upgrade. While the first use of MicroMegas in a high-energy physics experiment has been the COMPASS experiment in its tracker [31], the largest detector system instrumented with MicroMegas to date is the New Small Wheel built for the Phase-1 upgrade of the ATLAS experiment. One of the large general-purpose experiments at the LHC, the ATLAS detector is midway through its upgrade for the HL-LHC; the general goal of its upgrade is to maintain the Phase-1 performance at the higher background rates expected during Phase-2.

Several decay channels including low- p_T leptons, such as $H \rightarrow WW^* \rightarrow \nu\bar{\nu}\nu\bar{\nu}$ or $H \rightarrow \tau\tau$, will increase their sensitivity if the trigger momentum thresholds can be lowered; searches for processes with higher p_T muons ($> 100\text{ GeV}$), such as $Z' \rightarrow \mu\mu$, need an improved p_T resolution at higher background. The goal for the ATLAS muon system upgrade is to maintain a muon momentum resolution of the order of 1% and keep low trigger rates, allowing a reduction in p_T threshold. This has been achieved by replacing entirely the innermost detector station in the muon system, the Small Wheel, instrumented by MWPCs called cathode strip chambers (CSC).

The New Small Wheel (NSW) covers the pseudorapidity² region $1.5 < |\eta| < 2.4$ and is made of two detector technologies, resistive MicroMegas and small-strip thin-gap chambers (sTGC) – a class of resistive MWPCs using highly quenching mixtures [29]. Each of the two ATLAS endcaps has a NSW divided into 16 sectors (Fig. 2.5); in turn, each sector is made of two sTGCs enclosing four MicroMegas.

²In the reference system of a collider experiment, the pseudorapidity is $\eta = -\ln(\tan \frac{\theta}{2})$, where θ is the polar angle with respect to the beam line.

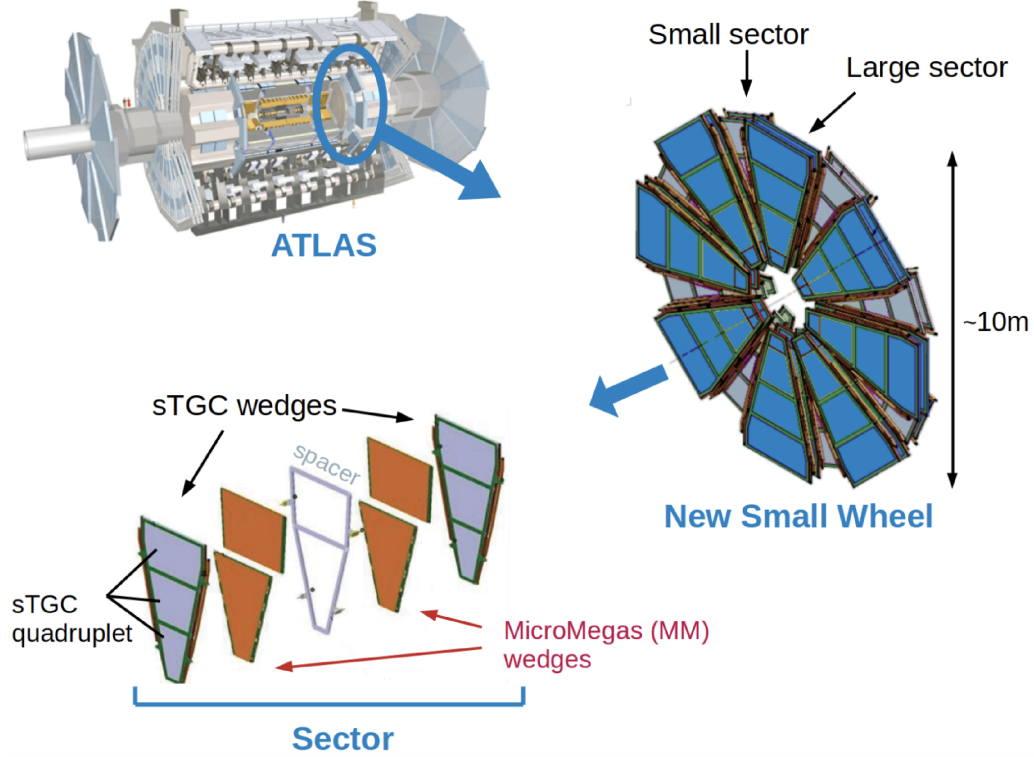


Figure 2.5: Position of the New Small Wheel in the ATLAS detector and layout of a NSW sector [32].

The main performance requirement of the NSW is to allow an angular resolution for muons at trigger level of the order of 1 mrad, which can be achieved with MicroMegas of about $100\text{ }\mu\text{m}$ space resolution. The readout plane of each MicroMegas is made of strips of about $400\text{ }\mu\text{m}$ pitch in the longitudinal direction with respect to the beam line, providing information in the $|\eta|$ direction; to provide the two-dimensional hit position in the wheel plane, the two external MicroMegas in each sector have readout strips oblique with respect to the central ones by a “stereo angle” of 1.5° in both directions.

The front-end ASIC of the NSW is the VMM3, a chip with programmable sensitivity (up to 16 mV/fC) and integration times (up to 200 ns) providing digital readout with 64 channels and signal arrival time information. The architecture of the front-end allows the MicroMegas to be operated in μTPC mode: this readout technique consists of recording the position and arrival time of each cluster and reconstructing a MIP track in the drift gap. Test beam studies showed that the μTPC mode allowed recovering the same space resolution for inclined particle trajectories as for perpendicular ones [33].

The NSW has been installed in ATLAS in 2021 and its commissioning has been performed in cosmic runs and in the first pp collisions of LHC Run 3 in 2022, showing that position

resolution and efficiency were in line with the requirements [32]; the present ongoing work is on the integration of the station with the ATLAS trigger.

2.2.2 Gas Electron Multiplier

The basic unit of a Gas Electron Multiplier (GEM) detector is the GEM foil [34], a thin sheet of polyimide covered on two sides by copper layers and etched with a regular pattern of thin holes (Fig. 2.6a). Common thicknesses are $50\text{ }\mu\text{m}$ for the polyimide layer and $5\text{ }\mu\text{m}$ for the copper coating, while the holes are usually in an exagonal pattern with $140\text{ }\mu\text{m}$ pitch; the shape of the holes (although depending on the etching technique) is typically biconical with inner and outer diameters respectively 50 and $70\text{ }\mu\text{m}$.

When a voltage difference is applied between the top and bottom electrodes, the charge multiplication is localized in the holes (Fig. 2.6b); in a single-GEM detector, most electrons extracted from the holes drift towards the anode driven by an induction field, while a fraction of them is collected by the bottom. In many gas mixtures, a GEM detector can be safely operated at a gain of 10^3 with an applied voltage difference around 500 V ; however, the layout of a GEM foil makes it suitable for cascading multiple amplification stages – three GEM foils being the most widely adopted layout. Foil cascading allows operating a single foil at low gains (of the order of 10), while the spreading of the avalanche across multiple holes minimizes the charge density, reducing the probability of discharge (Fig. 2.7). Triple-GEM detectors can be operated safely at gains between 10^4 and 10^5 , maintaining good space resolutions of the order of tens or hundreds of μm and energy resolutions of $15\text{--}20\%$ FWHM for low-energy x-rays.

The readout signal of a GEM detector is the one induced by the electrons created in the last foil and traveling in the “induction gap” towards the readout; the positive ions are collected from the top GEM electrodes and are shielded from the readout, so the rising edge of the signal is only made of electrons and has no ion tail.

The first high-luminosity particle physics experiment using GEM detectors has been COMPASS, a fixed-target experiment at CERN using muon and hadron beams from the SPS for hadron spectroscopy [35]. The COMPASS detector used 11 stations of two triple-GEM detectors each in its small-area tracker; each detector had an active surface of $31 \times 31\text{ cm}^2$ and a two-dimensional strip readout of $400\text{ }\mu\text{m}$ pitch and was read out by the APV25 front-end ASIC [36]. The main innovations introducing in the COMPASS GEM design were aimed at improving the detector stability towards discharges: the gaps between electrodes were standardized to $3/2/2/2\text{ mm}$ (Fig. 2.8a); the GEM foils were segmented in 12 sectors decoupled through resistors to decrease the capacitance of the gaps and, consequently, the energy released in discharges (Fig. 2.8b); the front-end chip was protected through diodes from discharges propagating through the induction gap. A point resolution of $70\text{ }\mu\text{m}$ with analog readout was measured for the COMPASS GEM tracker, as well as a time resolution of 12 ns . The COMPASS GEM tracker accumulated an integrated charge of 2 mC/mm^2 showing no signs of ageing.

One of the two Phase-1 LHC experiments to use triple-GEM detectors was TOTEM, the detector dedicated to the forward pp cross section measurement [37]. Made of two telescopes per endcap (T1 and T2) located in the forward region of the LHC interaction point 5, TOTEM complemented the CMS experiment in the pseudorapidity region $3 < |\eta| < 6.6$; each of the

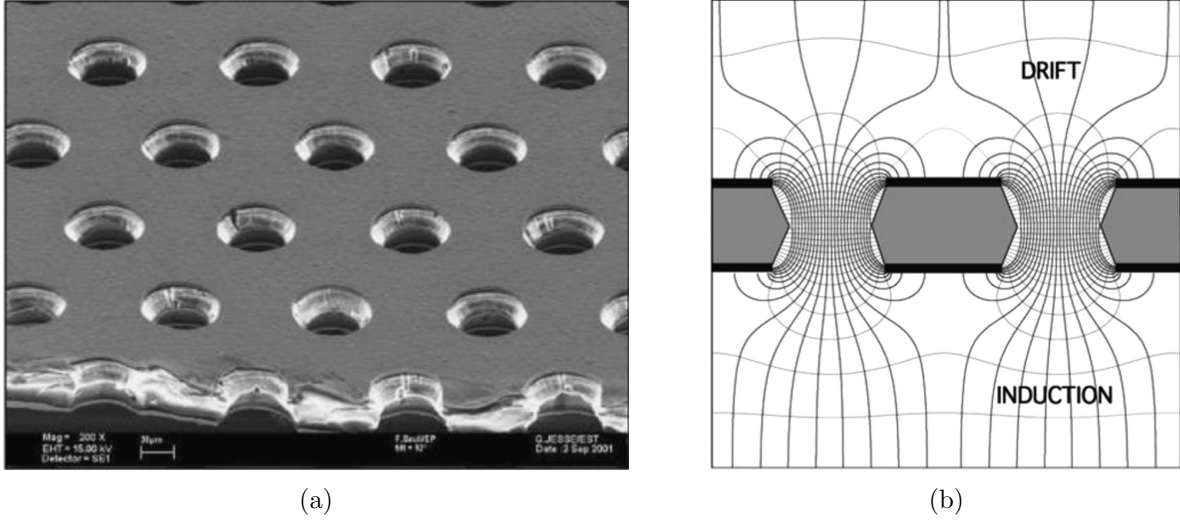


Figure 2.6: (a) Microscope picture of a GEM foil (b) Electric field and equipotential lines in a GEM foil [34].

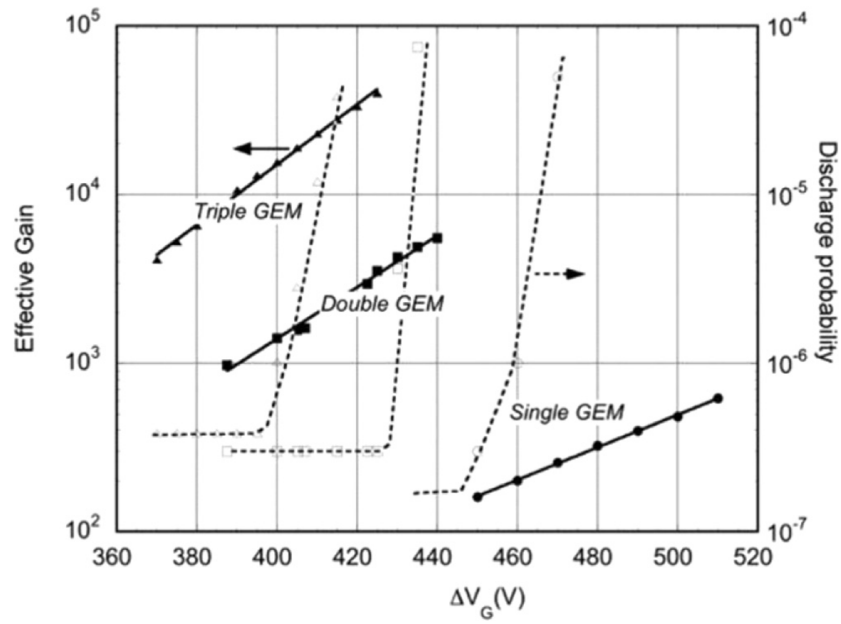


Figure 2.7: Effective gain and discharge probability of GEM detectors with different number of foils [34].

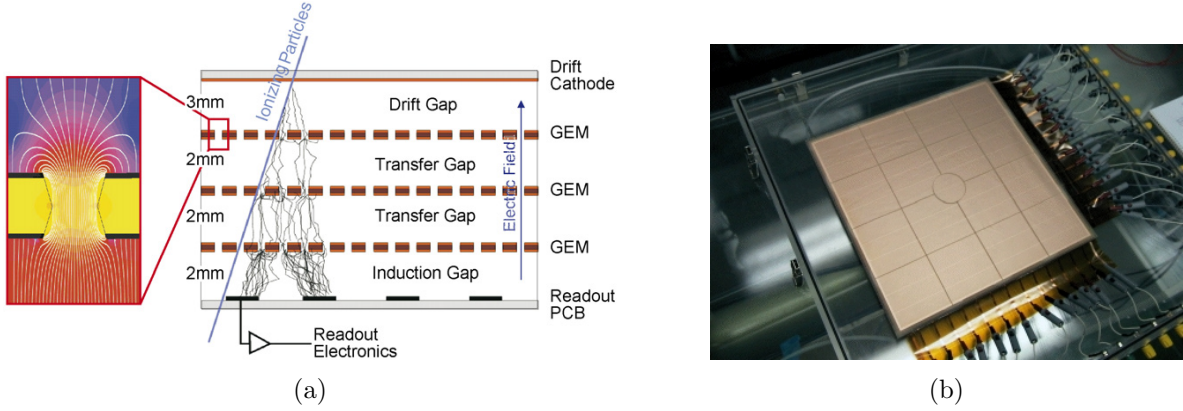


Figure 2.8: (a) Layout of the COMPASS triple-GEM detectors. (b) Segmentation of the COMPASS GEM foils [35].

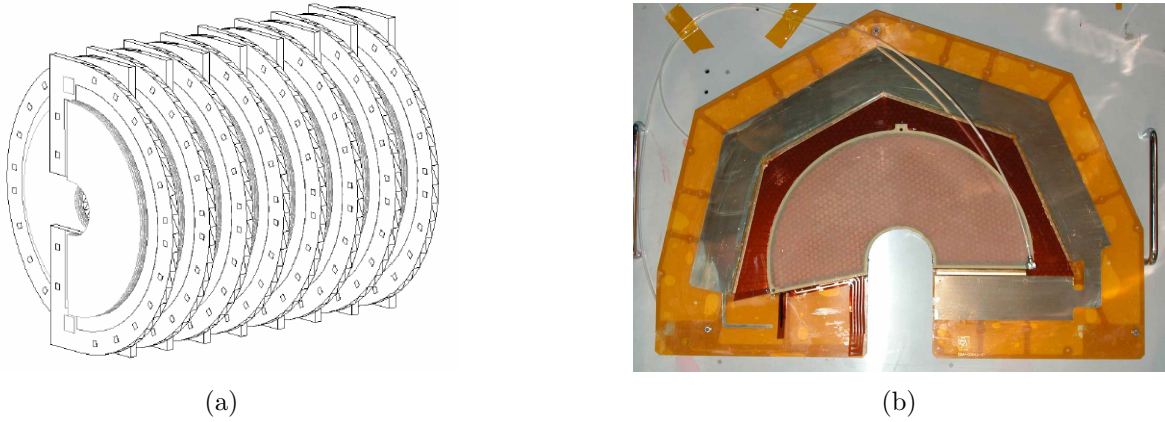


Figure 2.9: (a) Layout of the TOTEM T2 telescope. (b) GEM foil of the first prototype made for the TOTEM experiment [39].

two T2 telescopes was instrumented with 10 circular planes of triple-GEM detectors. The TOTEM GEM design followed the COMPASS one in the choice of the gap thicknesses and in segmenting the electrodes in quarters to prevent spark damage. The readout was made of a first plane of concentric strips of 90° aperture to be used for tracking and a second plane of radial pads for trigger; both layers were read by the VFAT2 front-end ASIC [38].

The second LHC experiment equipped with triple-GEMs has been LHCb, a forward detector dedicated at studying the CP violation and testing the standard models through rare decays from the $pp \rightarrow b\bar{b}$ process. The LHCb apparatus is made of layers extending from the LHC interaction point 8 for 20 m, made of a vertex detector (VELO), two RICHs for particle identification, an electromagnetic and hadron calorimeters and finally a muon spectrometer; in the LHC runs 1 and 2, the inner region (R1) of the first muon station (M1) was instrumented by triple-GEM detectors [40]. The M1R1 station was made of 12 chambers, each made of 2 triple-GEM detectors of $20 \times 24 \text{ cm}^2$; the total instrumented area was 0.6 m^2 . The detector

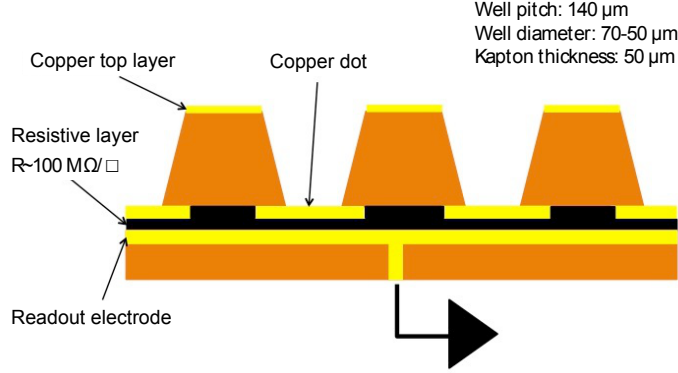


Figure 2.10: Layout of the amplification foil of a μ -RWELL [42].

anode was segmented in pads ($2.5 \times 10 \text{ cm}^2$ each) and read out by the CARIOCA front-end chip [41]. The LHCb improvements to the classical triple-GEM were focused on timing: an optimization of the gap thicknesses (with a 3/1/2/1 mm layout) and using a CF_4 -based mixture allowed reaching a time resolution of approximately 4 ns. The M1R1 station was able to stand for 10 years of LHC runs a background particle rate of 500 kHz/cm^2 , confirming the excellent longevity and rate capability of triple-GEM detectors.

2.2.3 μ -RWELL

A relevant example of resistive MPGD under active development is the μ -RWELL [42], whose schematic layout is shown in Fig. 2.10: the amplification region is defined by a “blind” GEM foil, i.e. a polyimide layer coated with a copper layer on top, etched with amplification holes and closed by a resistive electrode – typically diamond-like carbon (DLC) – on the bottom; the drift gap is defined by a cathode and the top electrode of the amplification layer. The amplified charge is collected by the resistive anode, separated by a thin ($\sim 50 \mu\text{m}$) pre-preg layer from the readout plane.

Due to the absence of an induction gap, the charge collection in the μ -RWELL is faster than a GEM, generating a sharp electron peak followed by an ion tail similar to a MicroMegas signal; The high resistivity of the anode (generally tens of $\text{M}\Omega/\square$) quenches the spark formation, making gains of the order of 10^4 reachable with a single amplification stage.

In the simplest μ -RWELL layout, gain drops of the order of 10% due to the ohmic behaviour of the resistive layer can be observed at fluxes of hundreds of kHz/cm^2 . To improve the rate capability the detector has to embed a dense network of points or lines connecting to ground; several alternative designs embedding conductive elements – made of copper vias or silver or copper grids – to ground the DLC have been developed [43]. The choice of the grounding schemes is mostly a trade-off between the ease of manufacturing and the reduction

in the active area; all layouts have been shown to be able to sustain rates of charged particles up to tens of MHz/cm² with small gain losses.

Since the amplification and readout layers of the μ -RWELL can be produced in a single piece, one of its potential advantages lies in its technology transfer and industrialization; in recent years the μ -RWELL has been suggested for the preshower and the muon detector of the IDEA experiment at FCC-ee and for the Phase-2 upgrade of the muon spectrometer of LHCb [44].

2.3 The CMS experiment: Phase-2 GEM upgrade

Designed mainly to investigate the Higgs sector, test standard model predictions and search and beyond-standard model physics on the TeV scale, the Compact Muon Solenoid (CMS) experiment is a general-purpose detector located at the LHC interaction point 5. The core of the CMS detector (Fig. 2.11) is a 3.8 T magnet made of a superconducting solenoid of length 13 m and diameter 6 m. The magnet encloses an inner tracker made of silicon microstrip detectors and, closer to the interaction point, silicon pixel detectors for reconstruction of the impact parameter and secondary vertex; the inner tracker has a point resolution of about 15 μ m and can achieve a p_T resolution of the order of 0.1% for high- p_T muons. Between the tracker and the solenoid are the two calorimeters: the inner one, the electromagnetic calorimeter, is made of PbWO₄ scintillators read out by avalanche photodiodes and vacuum phototriodes; the hadronic calorimeter is made of alternating layers of brass absorbers and scintillators read out by hybrid photodiodes, later upgraded to SiPMs.

The flux of the CMS magnetic field is closed by a steel return yoke, in which the muon spectrometer is installed (Fig. 2.12). The barrel region is instrumented by drift tubes (DTs), i.e. single-wire counters grouped in chambers (for a total of 250) of 100- μ m space resolution; the endcap is made of 540 multiwire proportional chambers with segmented cathode strips, called cathode strip chambers (CSCs), that provide a precision between 50 and 150 μ m. Both barrel and endcaps are also complemented by stations of dual-layer RPCs used for timing and triggering with coarser point precision and time resolution of 1.5 ns.

At the end of Run 2 in 2018, the LHC reached its design luminosity of 10^{34} cm⁻² s⁻¹ at 6.5 TeV beam energy, with a total luminosity of 160 fb⁻¹ delivered to CMS. The HL-LHC is expected to reach an instantaneous luminosity of 5×10^{34} cm⁻¹ s⁻¹, corresponding to an integrated luminosity of 3000 fb⁻¹, with a possible ultimate high-luminosity scenario up to 7×10^{34} cm⁻² s⁻¹ (for an integrated luminosity of 4000 fb⁻¹) (Fig. 2.13).

The upgrade of the CMS detector to cope with the increased luminosity and pileup will involve all of its subsystems: the inner tracker will be renewed for a better space resolution and geometrical acceptance; the barrel calorimeters are receiving an electronics upgrade, while the endcap calorimeters are being replaced by an high-granularity calorimeter (HGCAL) made of silicon detectors and scintillators. The level-1 trigger (L1) system is also being upgraded to allow faster momentum measurement, which will reduce the trigger rate.

Part of the upgrade of the muon system consists of the front-end and trigger electronics replacement (DTs, CSCs, RPCs) with components of increased bandwidth and radiation hardness; the GEM upgrade is instead the addition of new muon systems, aimed at improving

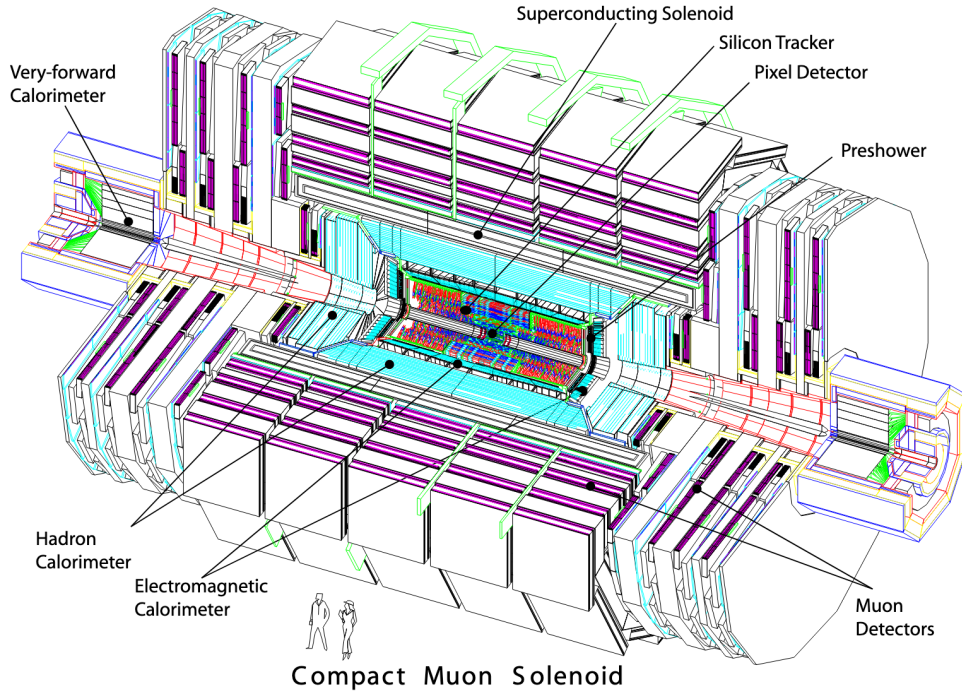


Figure 2.11: Layout of the CMS experiment [3].

the redundancy in the muon endcap by complementing the CSC stations and extending the geometrical acceptance of the muon spectrometer. Two additional RPC stations are also being installed with an improved layout (iRPC) in the forward region to complement the CSC stations located farthest from the interaction point.

2.3.1 GEM upgrade motivations and requirements

The CMS GEM upgrade consists of three new GEM stations, fulfilling different requirements: GE1/1, GE2/1 and ME0.

All CSC stations are complemented by close-by RPC stations, except for the four forward ones (ME1/1, ME2/1, ME3/1 and ME4/1) since the CMS RPC detectors in their original design cannot sustain the background rates at high pseudorapidity; at the same time, the very forward region is the one in which the magnetic bending of muons is the lowest, so the p_T measurement needs more hits to achieve a good resolution. The first two GEM stations, GE1/1 and GE2/1, will be placed in front of ME1/1 and ME2/1 and complement them in the local track reconstruction (Fig. 2.14): GE1/1 will cover the pseudorapidity region $1.6 < |\eta| < 2.15$, while GE2/1 will cover the region $1.6 < |\eta| < 2.4$.

The utility of GE1/1 and GE2/1 will be apparent especially at the Level-1 trigger level, since the increased lever arm for the momentum measurement will reduce the trigger rates without having to increase the p_T threshold. The local segments built using a GEM station and

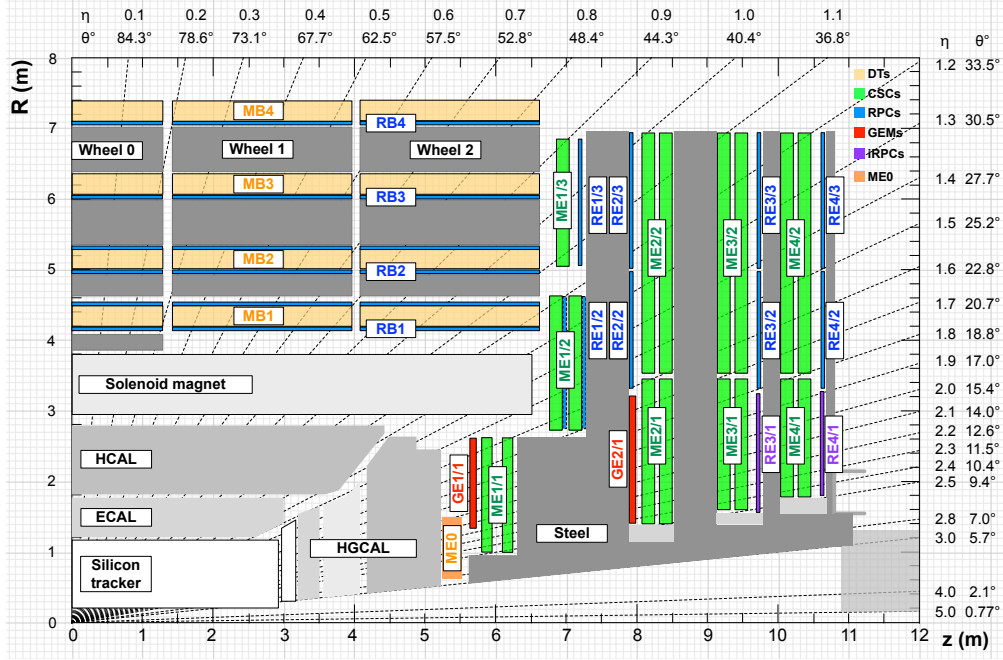


Figure 2.12: Quadrant of a section of the CMS muon spectrometer, showing the Phase-1 muon stations and the new stations after the Phase-2 upgrade (in red and orange) [45].

its CSC companion will be used as well to trigger at Level-1 on displaced vertices, which will be useful in searches for physics channels including neutral long-lived particles. Additionally, in case of longevity issues arising in the CSC stations, the GEM detectors will act as a backup.

The third GEM station, ME0, will be placed closer to the interaction point and will cover the pseudorapidity region $2 < |\eta| < 2.8$, thus extending the acceptance of the muon system. In the region $2.15 < |\eta| < 2.4$, covered already by another GEM and two CSC stations, ME0 will provide additional redundancy at the trigger level for muon p_T measurement and for displaced vertex triggering and reconstruction. In the region $2.4 < |\eta| < 2.8$, not covered by any other muon station, ME0 will be able to provide local segments for p_T measurement and will be able to complement the inner tracker in the muon reconstruction. The improved p_T resolution in the forward region and the extension to the very forward region will increase the sensitivity for physics channels including forward decay products, such as $H \rightarrow ZZ \rightarrow \mu\mu ll$.

The performance requirements for the three detector stations are similar:

- high and uniform efficiency (close to 100%) for MIPs;
- a space resolution of the order of 100 μrad in the radial coordinate along the beam axis;
- a time resolution below 10 ns to be able to identify hits within 1 bunch crossing (BX).
- longevity of the order of 1 C/cm^2 with no ageing effects.

An essential difference in requirements between ME0 and the other two stations is the rate capability, since the expected background particle rate in GE1/1 and GE2/1 ($1\text{--}2 \text{ kHz/cm}^2$)

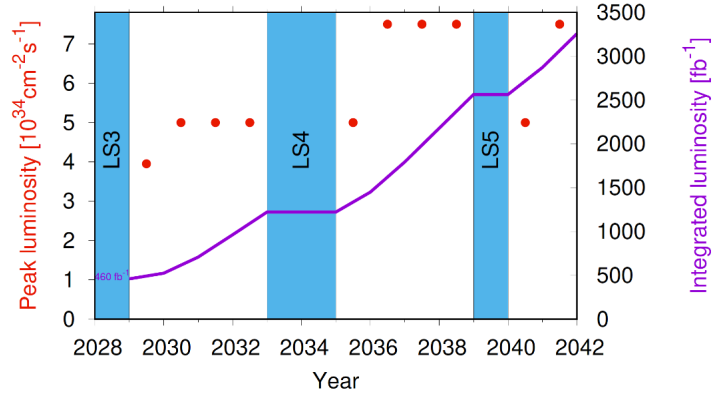


Figure 2.13: Expected delivered luminosity of the HL-LHC per year [46].

is much lower than in the ME0 case. The CMS Muon upgrade technical design report quotes a maximum value of 48 kHz/cm^2 for the expected ME0 background rate [45].

In all aspects, triple-GEM detectors are a suitable technology for the three new stations. In particular, the expected background flux in ME0 is lower by at least two orders of magnitude than the literature values for the triple-GEM rate capability, although always measured in small-area detectors.

2.3.2 Overview and status of the three CMS GEM stations

The GEM detectors for the CMS upgrade have a triple-GEM layout with gap configuration 3/1/2/1 mm; the anode is segmented in a single plane of radial strips read out by digital electronics. The gas mixture to be used for all detectors is Ar:CO₂ 70%:30%.

An R&D program has taken place since 2013 to optimize the triple-GEM technology for CMS and verify the compliance with its requirements.

A new scheme for the detector assembly has been formulated and is followed for the production of all three stations (Fig. 2.15): the GEM foils are attached with screws to an internal frame that is in turn fixed to an external frame through pull-outs. The pull-outs are then stretched with screws with a fixed force, maintaining the stretch mechanically. This self-stretching assembly avoids the use of glue – that slows down the process and might introduce pollutants into the gas – and internal spacer grids that introduce dead areas.

The three GEM stations share the same front-end electronics, based on the VFAT3 ASIC [48], a redesign from the TOTEM GEM electronics; The DAQ scheme, as shown in Fig. 2.16, is also similar in the three stations: each GEM detector is read out by several (between 12 and 24) VFAT3 chips that are controlled through a front-end concentrator board, the OptoHybrid (OH); the OH is responsible of the slow control communication with the VFATs, as well as receiving the DAQ and trigger data from the VFATs themselves. The OptoHybrid also receives and sends data to the back-end boards, placed in the CMS counting room; the back-end of the GE1/1 station is based on the pTCA standard, while the GE2/1 and ME0 back-end will be based on ATCA. A common data acquisition software allows the simultaneous operation of the GEM electronics by abstracting the different standards. An overview of the

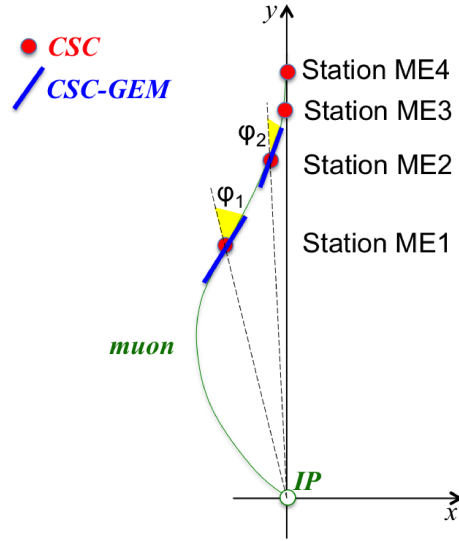


Figure 2.14: Trajectory of a muon showing the local segment reconstructed with the ME1/1 and ME2/1 stations in tandem with the GEM stations.

GEM front-end electronics and DAQ operation and performance is given in chapter 3.

Particular care has been taken in the GEM integration with electronics to the issue of discharges and their propagation towards the readout, as exemplified by the GE1/1 case.

2.3.2.1 Early Phase-2 upgrade: the GE1/1 station

The GE1/1 system is made of two disks (one in the positive and one in the negative endcap) of 36 “super-chambers” each (Fig. 2.17); in turn, each super-chamber is made of two stacked triple-GEM detectors covered by an aluminum chimney that acts as a Faraday cage. Two super-chamber types (long and short) alternate in each GE1/1 ring.

Each detector is trapezoidal, with an aperture of 10.15° , a narrow base of 23.1 cm and a

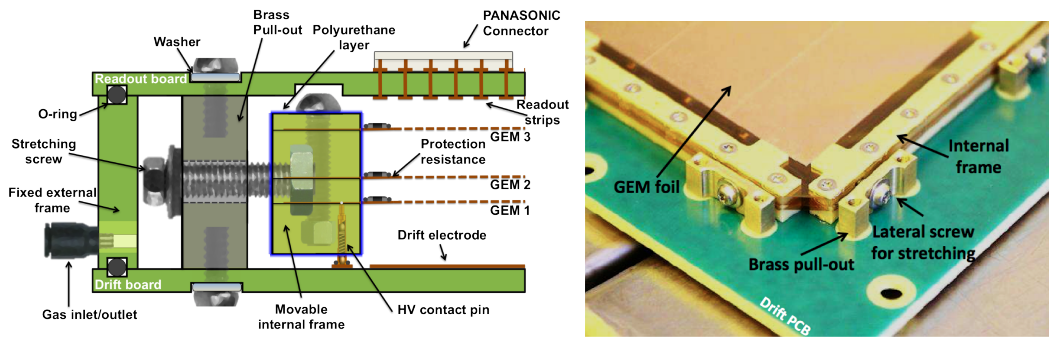


Figure 2.15: Scheme and picture of the self-stretching assembly technique used for the CMS GEMs [47].

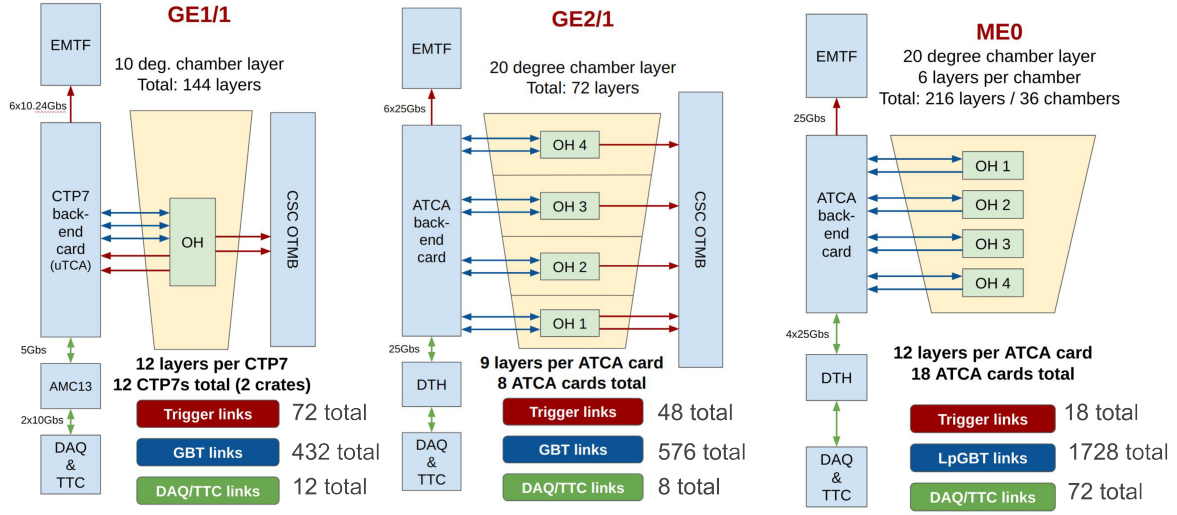


Figure 2.16: Overview of the electronics and back-end schemes for the three GEM stations.

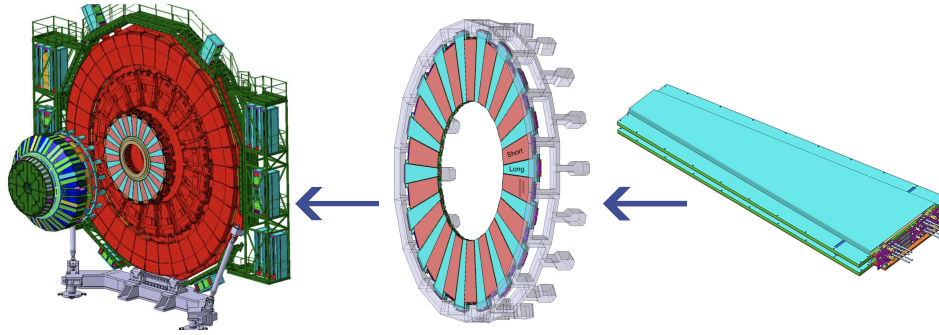


Figure 2.17: From left to right, position of GE1/1 in the first muon disk, layout of the GE1/1 disk and picture of a GE1/1 super-chamber [49].

height – respectively for a short and a long detector – of 106.1 cm and 120.9 cm. The top electrode of each GEM foil is segmented in 40 sectors along the longitudinal direction for the short chambers and in 47 sectors in the long chambers; the sectors of each foil are connected to the power supply channel through 10 M Ω resistors. The bottom electrode of the GEM foils is not segmented. The segmentation and the presence of quenching resistors helps reducing spark damage, prevents its propagation and reduces the current drained by the foil in case of a permanent short circuit between top and bottom (see chapter 3).

Before the GE1/1 large-scale production, a demonstrator (also called “slice test”) made of five super-chambers was installed in CMS and operated during Run 2 to gain operational experience of the full system, although with non-final electronics and software. One of the main findings of the slice test was a high number of front-end channel losses, later related to discharges in the detector that destroyed the VFAT3 input bondings. The mitigation strategy chosen after laboratory tests with high-energy sources [50] consisted of modifying the layout

of the VFAT3 packaging by adding a $470\,\Omega$ protection resistor in series of each channel input.

GE1/1 is part of the “early Phase-2 upgrade”: the GE1/1 detectors have been assembled between 2018 and 2020 and installed in CMS between 2019 and 2020. Before the installation, each detector passed a sequence of ten quality assurance tests aimed at [47]:

- verifying the stability of the GEM foils to high voltage in CO_2 before and after the detector assembly;
- verifying the detector gas tightness;
- measuring the gain of each detector with analog electronics and its gain uniformity with high-granularity readout using the APV25 chip;
- testing the front-end electronics once installed on the detector;
- measuring the track-based efficiency trend of the super-chamber as a function of its bias point in a cosmic stand to determine its optimal working point.

Fig. 2.18 shows the average efficiency distribution measured with cosmics of all the GE1/1 detectors installed in CMS [51]. One of the unexpected effects observed on several detectors, especially long super-chambers, was a lower efficiency in the center of the detectors with respect to the borders; this “basin effect” was traced to a bending in the readout board, that increased the central thickness of the induction gap and consequently slowed the signal trailing edge. An impact of the basin effect on the GEM time resolution uniformity was also observed during the GE1/1 commissioning.

After the installation and integration in the CMS environment, the GE1/1 detectors have been operated during the end of the LHC LS2 in the CMS cosmic runs at zero tesla (CRUZET) and at four tesla (CRAFT), then during Run 3 in 2022. The efficiency of the detector in CMS has been measured with cosmics and during the first proton-proton collisions using the muon segments reconstructed by the ME1/1 station, propagated through the active area of the GEM detectors; Fig. 2.19 shows the efficiency of the GE1/1 detectors measured at the beginning of Run 3 [52, 53].

GE1/1 is already used in the offline reconstruction during Run; its integration in the L1 trigger is currently ongoing.

2.3.2.2 The GE2/1 station

Each of the two GE2/1 endcaps will be made of 36 super-chambers of opening angle 20° each; as for GE1/1, each super-chamber will be made of two triple-GEM detectors with bases 53.3 cm and 117.4 cm and height 183.3 cm. For ease of assembly and test, each detector is divided along its bases in four smaller modules: the modules of the front layer in each super-chamber are labeled from M1 to M4, while the back layer modules are from M5 to M8 (Fig. 2.20).

The design of a GE2/1 GEM foil is similar to GE1/1, with the difference that the bottom GEM electrode is also segmented and a $100\,\text{k}\Omega$ quenching resistor has been introduced to decouple the bottom sectors from the power supply for the GEM foils 1 and 2; the third GEM

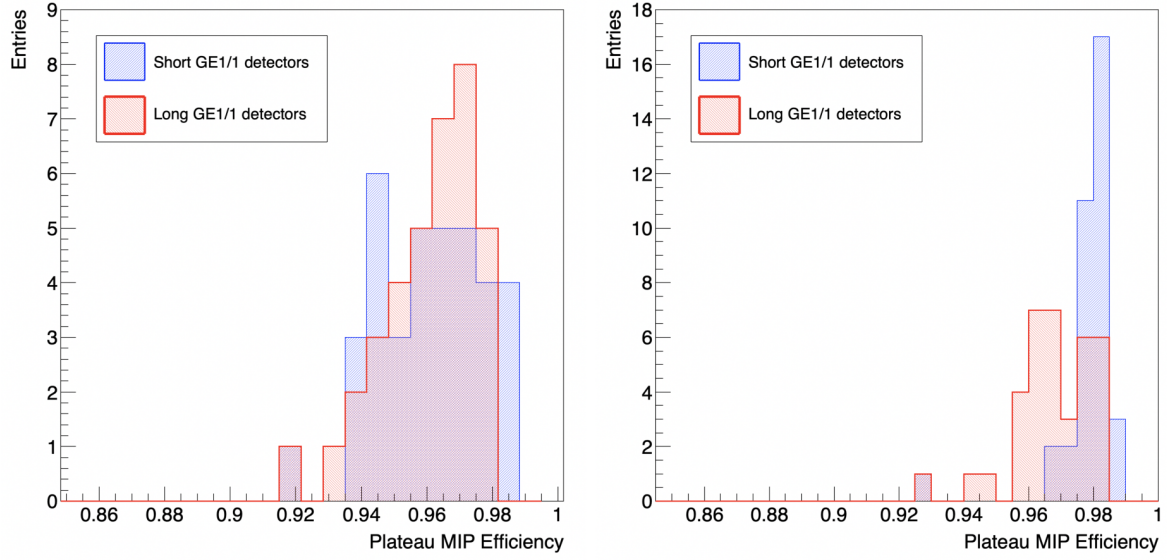


Figure 2.18: Efficiency distribution measured in the GE1/1 cosmic stand for all the GE1/1 super-chambers of the negative endcap (left) and of the positive endcap (right).

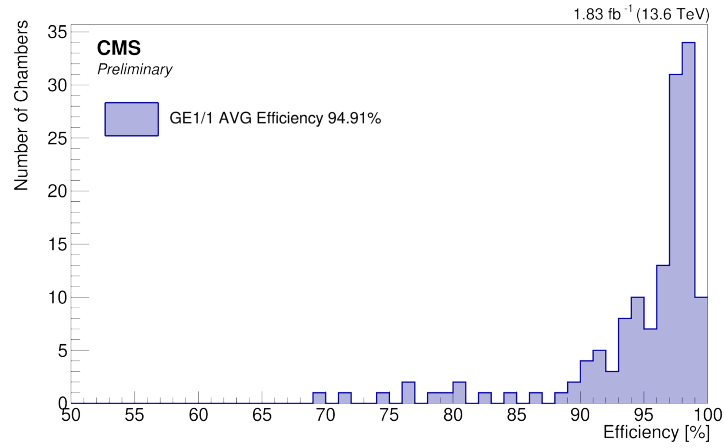


Figure 2.19: Distribution of the efficiencies of all GE1/1 detectors measured with muons in Run 3 [52].

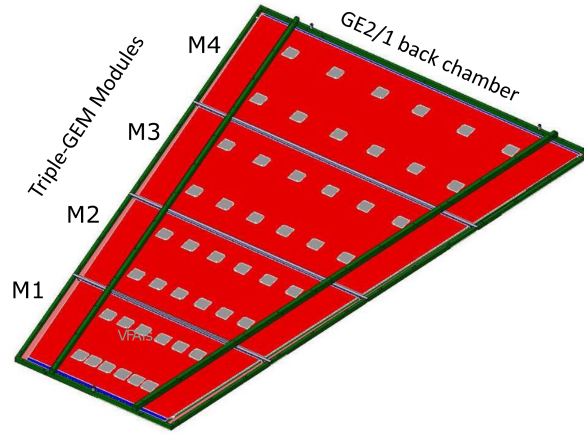


Figure 2.20: Layout of a GE2/1 detector and its division in modules [45].

foil has still a segmented bottom electrode for ease of production, but the quenching resistors are shorted.

GE2/1 design changes. Two of the main production improvements in GE2/1 with respect to GE1/1 concern its response uniformity and the protection of its readout electronics.

To avoid the basin effect observed in GE1/1 due to the readout board bending, the GE2/1 detectors include central pillars between the GEM foils and in the gap that ensure the readout board planarity. Gain measurements with high granularity on the first GE2/1 detectors assembled have shown an improved uniformity with respect to GE1/1 in the central detector region.

The second main improvement in the GE2/1 design is the VFAT3. While the VFAT3 circuit has not changed, the VFAT3 PCB for GE2/1 has been assembled on a plug-in card (Fig. 2.21a). The most important differences between the GE1/1 hybrid and the GE2/1 plug-in card are:

- while the GE1/1 VFAT3 is mounted on a hybrid high-density interconnect (HDI) PCB, the GE2/1 chip is mounted on a HDI flex-rigid PCB; the flex part prevents issues in the alignment of the chip on the detector observed during the GE1/1 production;
- in GE1/1, the naked chip was mounted on the PCB, while the GE2/1 VFAT3 PCB contains a packaged chip, i.e. the chip die is mounted on an intermediate PCB to ease the board production;
- to increase the channel protection to discharge damage, the input protection of the chip (which in GE1/1 was a $470\text{ M}\Omega$ series resistor) was initially replaced by a decoupling circuit made of a $100\text{ k}\Omega$ resistor to ground and a 1 nF capacitor (Fig. 2.21b). However, after realizing during the late stages of detector integration that the new input circuit had a higher discharge probability than the previous one, the $470\text{ }\Omega$ resistor protection was restored.

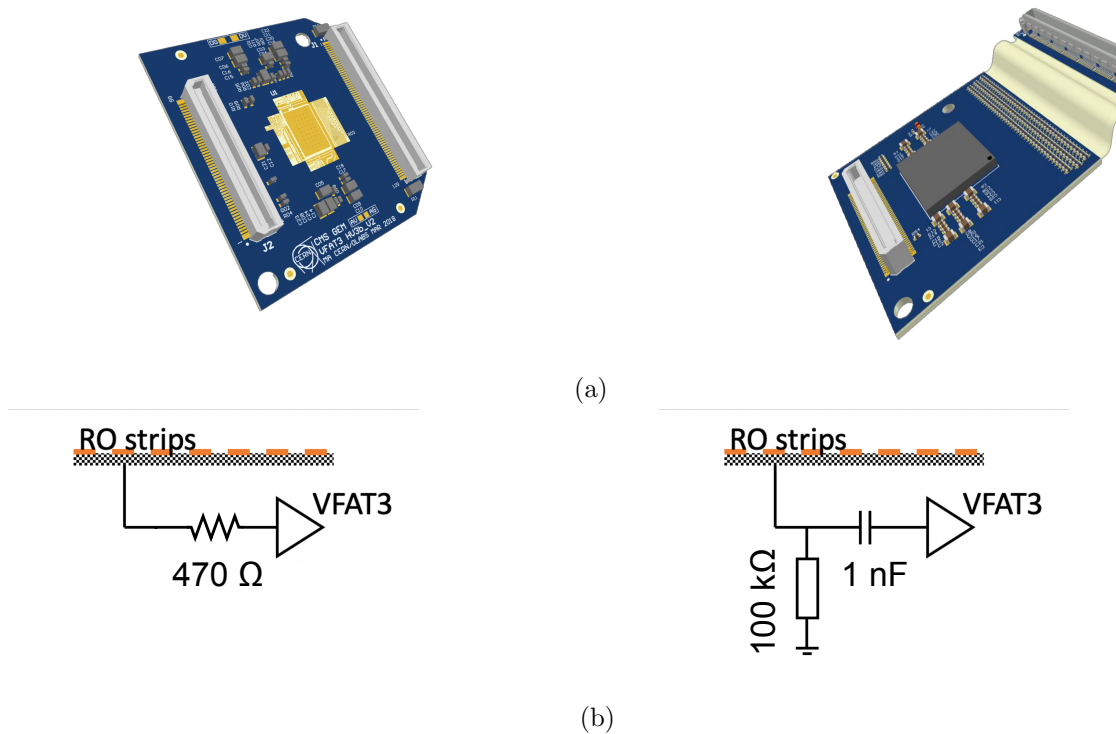


Figure 2.21: (a) Picture of a VFAT3 hybrid (left) and a plug-in card (right). (b) Protection resistor circuits in the VFAT3 hybrid for GE1/1 (left) and in the VFAT3 plugin card proposed for GE2/1 and ME0 (right).

A GE2/1 demonstrator made of a single detector (modules M1 to M4) was installed in CMS during Run 3, in the 2021 year-end technical stop (YETS), integrated with the CMS software and operated in the first months of Run 3 collisions. Fig. 2.22 shows an occupancy plot of the GE2/1 demonstrator during a run.

The production of the GE2/1 system is ongoing; the installation of the positive disk is planned for the 2023 extended year-end technical stop (EYETS), while the second disk is planned for installation in LS3.

2.3.2.3 The ME0 station

Each ME0 endcap will be made of 18 stacks (Fig. 2.23). Unlike GE1/1 and GE2/1, an ME0 stack will be made of six triple-GEM detectors, in order to build stand-alone segments since no companion CSC station will be available. Each ME0 detector is a trapezoid of aperture of 20° , bases 23.6 and 51.4 cm and height 78.8 cm.

The baseline GEM detector design of ME0 is similar to the GE2/1 case; some of the design optimizations adopted for ME0 are among the subjects of this thesis work and will be discussed in the next chapters. The front-end ASIC of the ME0 station is the VFAT3 in

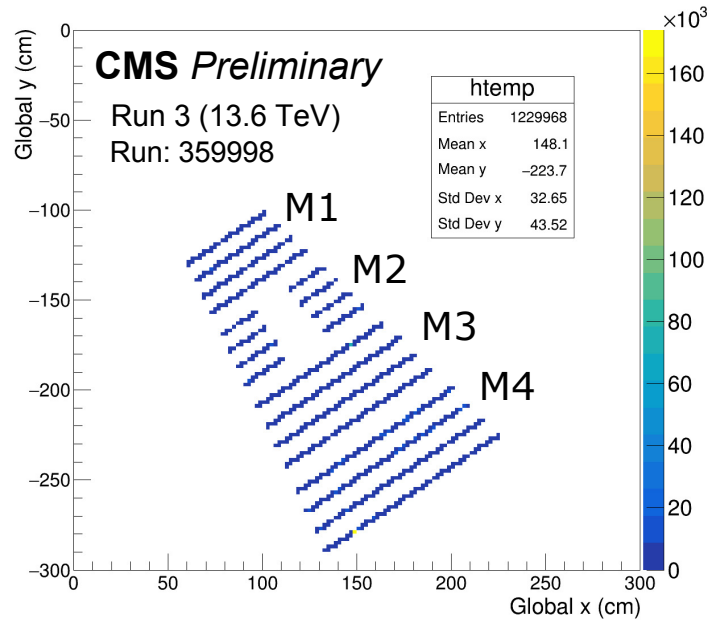


Figure 2.22: Occupancy plot in the GE2/1 demonstrator during Run 3. The empty space is due to four VFAT3 that lost connection with the back-end during the run.

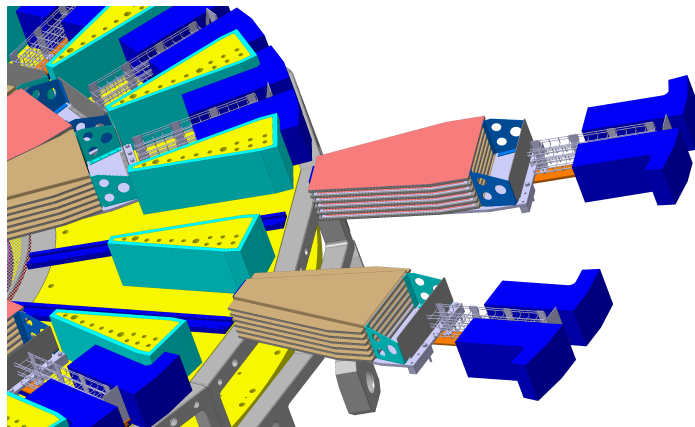


Figure 2.23: Scheme of two ME0 stacks (each made of size triple-GEM detectors) during installation in the ME0 endcap nose [45].

the same packaging as GE2/1. The main difference in the ME0 electronics from the first two GEM stations will come from radiation-hardness compliance, as no FPGA will be present in the front-end components; additionally, the ME0 back-end board (the X2O) will need to generate its own trigger primitives in the FPGA.

The integration of a prototype ME0 stack with the final front-end electronics is ongoing in the beginning of 2023. The production of ME0 is scheduled to begin in 2024; the ME0 installation is foreseen for LS3.

Chapter 3

First performance of the Phase-2 CMS GEM detectors measured with beam

The following sections outline the preparation, analysis workflow and results of two test beam campaigns carried in the CERN North Area in 2021 and 2022 for the measurement of the final performance of the CMS Phase-2 GEM detectors with their final front-end electronics and data acquisition software with particle beams. The main goal of the test beam campaigns is the assessment of the GE2/1 and ME0 detector performance with final front-end electronics and validation of detector with respect to the CMS Phase-2 GEM Upgrade TDR requirements.

The main detectors under test, described in the next section, are a GE2/1 “production” detector, i.e. assembled for the final installation in CMS, and an ME0 prototype of near-final design; the GE2/1 module operated in the test beam is an M1.

My activity consisted in completing the integration of the GE2/1 and ME0 detectors and electronics, adapting the existing data acquisition software to the Phase-2 GEM electronics, the calibration and commissioning of the setup, supervising the data taking, developing an offline reconstruction framework and performing the analysis.

3.1 Design of the GE2/1 and ME0 detectors

The GE2/1 and ME0 system share the same detector technology and front-end ASIC; the main differences between the two systems are related to the optimization of the ME0 detector and its electronics for operation in high rates and accumulation of high doses. The next sections describe in detail the detector layout and its front-end electronics.

3.1.1 High voltage distribution and GEM foil sectorization

As mentioned in chapter 2, large-area GEM detectors have been shown to be very sensitive to damage in the GEM foils or the readout electronics due to discharges occurring in the GEM holes and possibly propagating from one foil to the other. Two major mitigation strategies

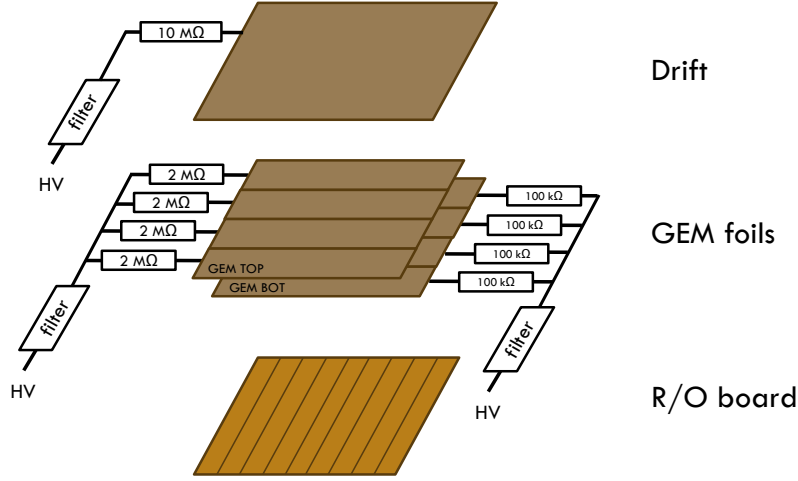


Figure 3.1: High voltage scheme of a CMS GEM detector with segmented GEM foils; only one GEM foil is shown.

have been adopted on the GEM foil design for the Phase-2 GEM detectors to prevent discharge damage:

- the top and bottom electrode of each GEM foil are segmented in electrically independent sectors, the area of each sector always being lower than 100 cm^2 . The segmentation lowers the capacitance of two electrodes facing each other in the same GEM foil or in the same gap, thus decreasing the energy stored by the gap ($E = \frac{1}{2}CV^2$) and the current flowing on the electrodes when they discharge through a spark;
- each sector is connected to the power supply through a protection resistor of resistance between $100 \text{ k}\Omega$ and $10 \text{ M}\Omega$. In case of a spark occurring in the gas, the increased current flowing to the electrode (of the order of a few μA) causes a voltage drop of a few volts in the resistor, which lowers the voltage on the electrode with respect to the supplied potential and quenches the discharge.

Additionally, the quenching resistors decouple the foil sectors, to allow powering the different sectors of a GEM foil with a single high voltage channel. Finally, in case of short circuit in a GEM hole, the resistors limit the current drained by the corresponding sector.

The generic high voltage distribution scheme of the detectors is shown in Fig. 3.1. Each GEM foil is powered from a separate channel of the high voltage board; an RC filter – added to reduce noise in the readout electronics coming from the high voltage boards – is connected to the channel, which is then split to supply voltage to each sector.

The sectorization of the GE2/1 detector is shown in Fig. 3.2a; the sectors are divided along the η direction, are all trapezoidal and of equal surface of 100 cm^2 . The sectorization of the ME0 detector in the design in use in the test beam, shown in Fig. 3.2b, is instead along the ϕ direction, azimuthal with respect to the LHC beam line. The change in sectorization between GE2/1 and ME0 is a result of the design optimization of the ME0 detector for high rates, as will be discussed in chapter 4.

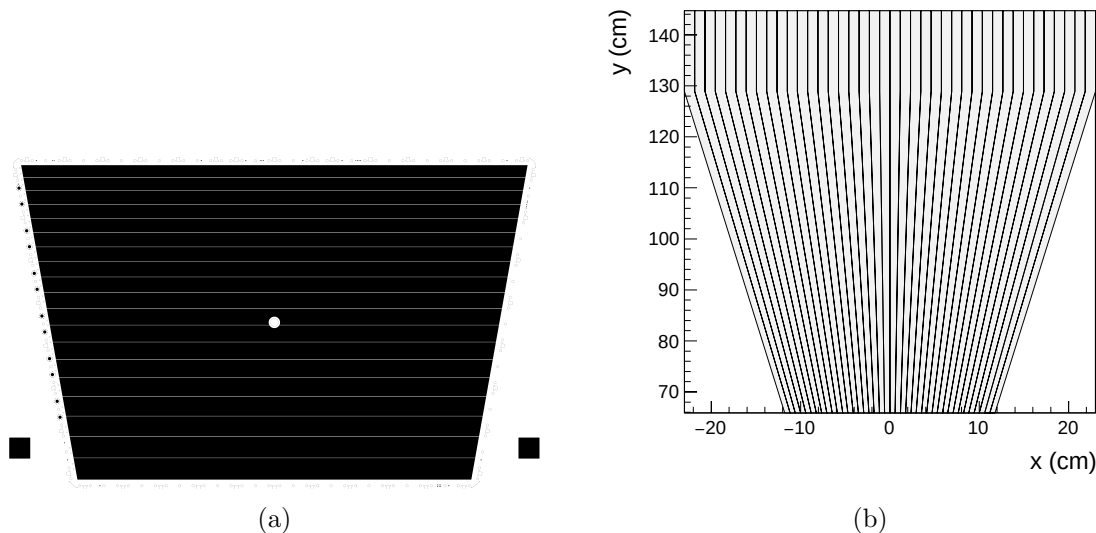


Figure 3.2: Segmentation of a GEM foil of a GE2/1 M1 detector (a) and an ME0 detector (b).

One of the goals in the test beam has been to compare the performance of GEM detectors manufactured with the traditional *blank* segmentation with prototypes using the *random hole* segmentation, a proposed technique to increase the ME0 acceptance; a more detailed discussion on the production of GEM foils with segmentation and its effect on the efficiency is presented in appendix A.

3.1.2 Read-out plane

GEM detectors are expected to provide tracking in the CMS muon spectrometer with a resolution of the order of $100\mu\text{rad}$ in the ϕ direction and with coarse accuracy in the η direction. Therefore, the anode planes of the Phase-2 detectors are segmented in 384 radially distributed strips along the azimuthal direction (Fig. 3.3); along the longitudinal direction, the read-out board is divided in partitions of a few cm height to provide a coarse position measurement in the η direction and reducing the strip length to lower the electronic noise.

The read-out board of the GE2/1 M1 module irradiated in the test beam is divided in four eta partitions of 97 mm height each; the strip pitch is $922\mu\text{rad}$, for an expected space resolution of $266\mu\text{rad}$. The readout plane of an ME0 detector is instead divided in eight eta partitions of 98 mm each, with strip pitch of $738\mu\text{rad}$ and expected space resolution of $213\mu\text{rad}$.

3.1.3 Front-end electronics

The on-detector electronics of the Phase-2 GEM detectors provides two readout paths for tracking with full strip granularity and trigger information with two-strip granularity in single-data rate. The front-end electronics is made of three essential components: a front-end ASIC

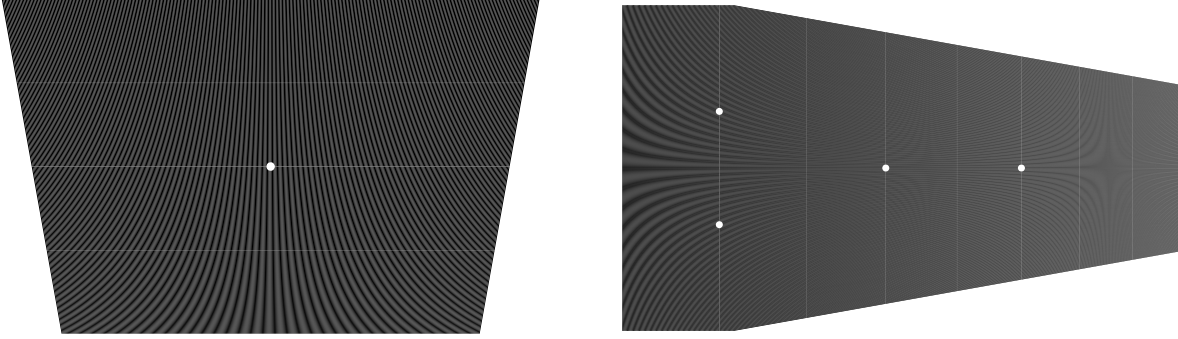


Figure 3.3: Design of the read-out boards of the GE2/1 M1 module and of the ME0 detector, showing the coarse segmentation in eta partitions and the strip segmentation.

(VFAT3) responsible of the strip readout, a concentrator board (OptoHybrid) sending the readout data to back-end and a PCB (GEB) distributing power and electrical links to the front-end components.

3.1.3.1 The VFAT3 ASIC

The front-end readout chip is the third version of the VFAT3 (Very Forward ATLAS and TOTEM) ASIC [48]. As mentioned in chapter 2, the design of the VFAT3 chip is the same for the three GEM stations, with variations in the input protection circuit and in the external PCB; both GE2/1 and ME0 use the VFAT3 plug-in-card.

Each VFAT3 has 128 independent readout channels; the schematic block diagram of a single channel is shown in Fig. 3.4. The front-end can be divided into an analog section, made of a charge-sensitive preamplifier, a shaper and a discriminator, and a digital part responsible of buffering and communication. The chip is completed by a CBM (calibration, bias and monitoring) unit for the control and calibration of each chip component.

Analog front-end. The parameters of the analog channel front-end (Fig. 3.5) are optimized for the expected shape of a triple-GEM signal (as simulated in Fig. 3.6). The charge-sensitive preamplifier is a sliding-window integrator of sensitivity programmable between 16 and 60 mV fC^{-1} by adjusting the feedback resistor and capacitance; the shaper load capacitance is adjustable to allow front-end peaking times programmable between 25 and 100 ns. As the expected input signal duration varies between 10 and 100 ns, integrating over the entire signal duration allows, in theory, maximum time resolution thanks to the time-walk compensation carried by the discriminator. The optimization of the analog front-end configuration for GEM timing is outside the goals of this thesis [54].

Comparator. The VFAT3 discriminator (Fig. 3.7) is a constant-fraction discriminator (CFD) designed to optimize timing by compensating for the time walk due to the fluctuations in the signal amplitude. The actual implementation of the discriminator is made of two separate branches: a *timing* branch, containing the zero-crossing comparator (ZCC), and an *arming*

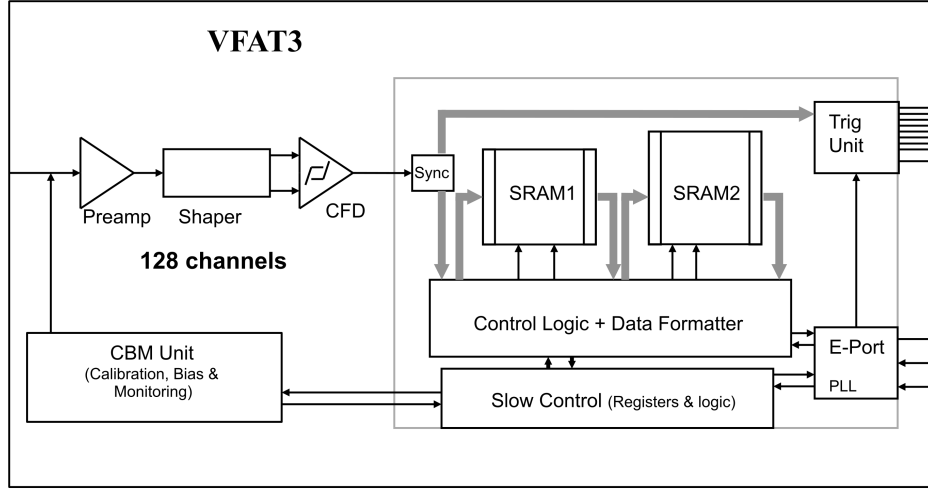


Figure 3.4: Block diagram of a VFAT3 channel architecture.

branch, made simply of a comparator that enables the timing path. The simplified behaviour of the CFD is the following:

1. the analog signal is shaped by a passive network of RC filters to a bipolar signal;
2. a small voltage offset is added to the bipolar signal to avoid firing the zero-crossing comparator on noise;
3. when the bipolar signal first crosses the programmable ZCC threshold, the offset is removed;
4. when the bipolar signal crosses the zero level, the output of the CFD is enabled.

The time of arrival of the ZCC output signal is independent of the input signal amplitude.

Digital block and communication. The digital part of the VFAT3 is responsible of synchronizing the discriminated data with the 40 MHz LHC clock and piping them to a buffer for back-end transmission. The synchronized digital signal is split in a trigger path and a data path. In the former, the digital information from two neighbouring strips and combined in OR and the resulting synchronous bit (*s-bit*) is sent directly to the OptoHybrid for further compression before being transmitted to the CMS trigger logic. The data branch is instead a variable latency path; the synchronized digital signal is first extended in time by a programmable number of clock cycles (the *pulse stretch*), then stored at the beginning of a circular buffer (SRAM1) of 1024 bit depth; at each clock cycle, the signal advances by one bit in the buffer. When the chip receives an external level-1 accept (L1A) trigger signal, the bit stored at a specified depth in the SRAM1 is copied to a second buffer (SRAM2); the latter is a FIFO where the data are identified by their bunch counter (BC) and event counter (EC) before being transmitted to the OptoHybrid (the data format of an encoded VFAT3 event is described in section 3.5.1). The position of the bit to be copied between the two buffers at

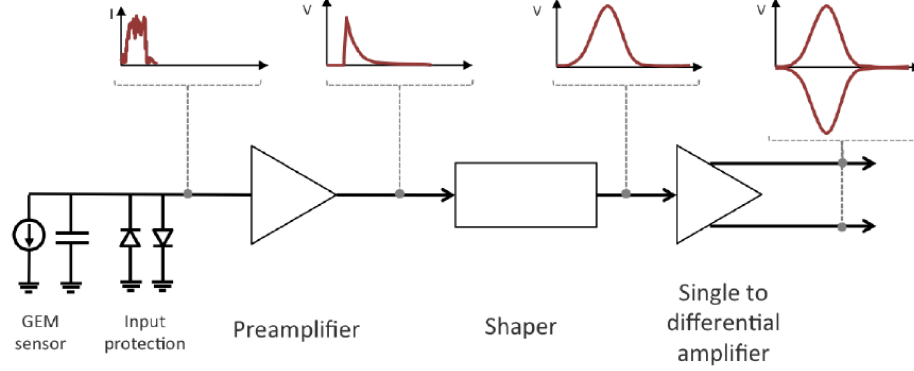


Figure 3.5: Block scheme of the VFAT3 analog front-end.

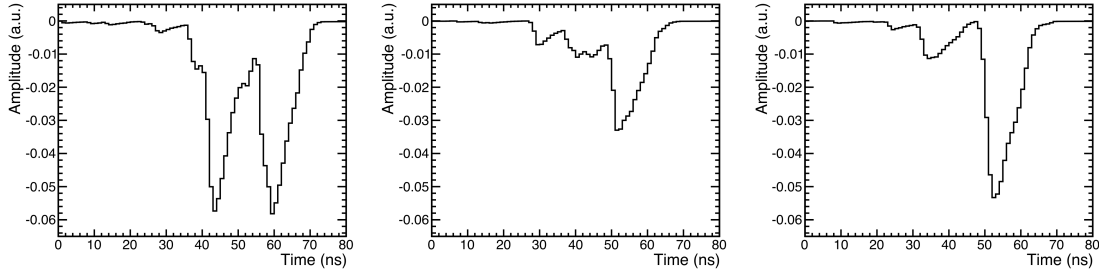


Figure 3.6: Examples of simulated signals from a triple-GEM detector [55].

the arrival of an L1A is called *latency* and represents the delay between the time of formation and arrival of the external trigger and the signal formation and processing in the detector and front-end.

3.1.3.2 The OptoHybrid

The front-end concentrator board, the OptoHybrid (OH, Fig. 3.8), has two main roles:

- receiving the VFAT3 data and transmitting them to the back-end after compression;
- sending slow-control commands from the back-end to the on-detector electronics.

Although the design of the OptoHybrid changes between GE2/1 and ME0, the typical architecture of the communication between back-end and readout front-end is common between the two and is schematized in Fig. 3.9: the communication between detector and back-end follows the CERN standard defined by the GBT (GigaBit Transceiver) protocol [56]. The OptoHybrid board contains GBT ASICs used to communicate with the VFATs; the data transmission between the two happens through electrical links (eLinks) using differential low voltage signals defined by the CERN Low Power Signaling (CLPS) standard. The GBT ASIC

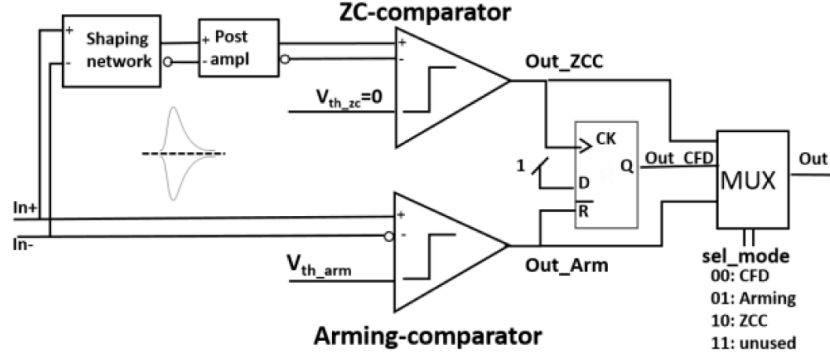


Figure 3.7: Scheme of the VFAT3 constant fraction discriminator.

used in the GE2/1 OptoHybrid is the GBTX, which supports bidirectional communication at 4.8 Gbps speed, while the ME0 OptoHybrid uses the newer lpGBT (low power GBT), the CERN-defined baseline for the Phase-2 upgrade of the LHC experiments, which supports data transmission up to 10.24 Gbps.

The communication between on-detector electronics and back-end is carried by the Versatile TRansceiver (VTRX), an electro-optical transceiver developed by the Versatile Link project. The GE2/1 OptoHybrid uses the VTRX chip, replaced by the upgraded VTRX+ in ME0; the former ensures a data transmission rate of 4.8 Gbps, while the latter can reach up to 5.12 Gbps in reception and 10.24 Gbps in transmission.

Besides what has been already mentioned, the GE2/1 and ME0 OptoHybrid differ mostly in the compliance with the CMS radiation hardness requirements. The GE2/1 OptoHybrid board contains a Xilinx Artix-7 FPGA, used for the compression and first processing of the trigger data received from the VFAT3 s-bit line (see section 3.1.3.1); the trigger data are then sent to the CMS Muon trigger back-end for the generation of the trigger primitives through a separate optical transmitter (the VTTX chip). In the ME0 OptoHybrid no FPGA is present, in order to comply with the higher expected dose and the trigger data are sent to the GEM back-end through the VTRX+; the trigger primitives are generated in the ME0 back-end FPGA.

3.1.3.3 The GEM electronic board

The VFAT3 and OptoHybrid are mounted on the detector through the GEM electronic board (GEB), a PCB attached to the detector readout board that routes the data and power lines and works as mechanical support for the front-end electronics. The low-voltage power provided to the GEB is distributed to DC-DC converters (FEASTs) and from those to the other components. The design of the GE2/1 and ME0 GEBs are shown in Fig. 3.10: a GE2/1 GEB of any module kind (from M1 to M8) hosts one OptoHybrid and powers 12 VFATs, while an ME0 GEB is made of two separate PCBs along the η direction – called *wide* and *narrow* GEB; each GEB is powers two OptoHybrids and 12 VFATs.



Figure 3.8: Pictures of the GE2/1 (left) and ME0 (right) OptoHybrids.

3.2 Setup of the CMS GEM Phase-2 test beam

The layout of the test beam setup is shown in Fig. 3.11. The two main detectors under test are the GE2/1 and ME0 detectors; two random-hole segmented prototypes (a rectangular detector and an ME0 detector) are also tested. The detectors under test are enclosed in a tracker made of four 10×10 triple-GEM detectors. Three $10 \times 10 \text{ cm}^2$ scintillators in coincidence (one in front of the setup, two in the back) read by photomultipliers provide trigger to the beam.

3.2.1 The high-resolution $10 \times 10 \text{ cm}^2$ tracker

The tracking detectors have been designed targeting a $75 \mu\text{m}$ point space resolution.

Each tracking detector is a square of 89 mm side (Fig. 3.13). The GEM foil gaps are the same as for the CMS GEM detectors and the read-out board is made of two planes of 358 perpendicular strips each, for a pitch of $250 \mu\text{m}$; the read-out board design is shown in Fig. 3.12.

The tracking detectors are read out by VFAT3 hybrids, three connected to each strip plane as shown by the scheme in Fig. 3.14. A custom-made adapter board allows connecting the VFATs on the tracker readout board to the slots of a GE2/1 GEB through external cables, so the VFATs of the entire tracker are controlled by two GE2/1 GEBs, an M6 and an M7 (each GEB reading out two tracking detectors).

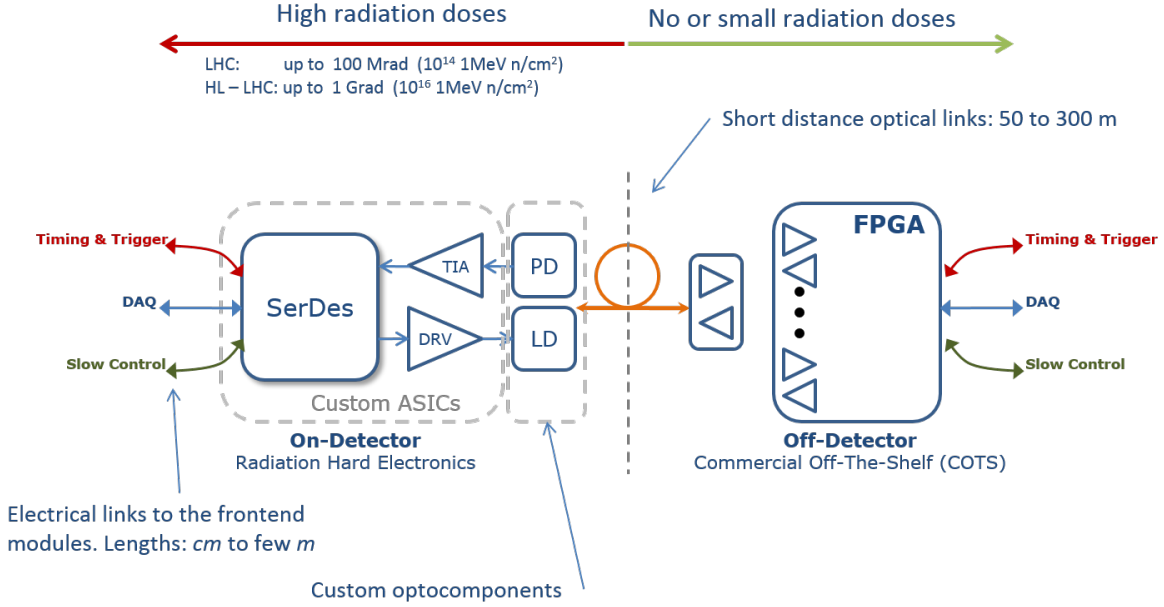


Figure 3.9: Architecture of the GBT link [57]. The GBT chipset connects the front-end electronics with the counting room and is made of three parts: the GBT ASIC itself, a transmitter and a receiver. The transmitter is a driver (DRV) for a quad laser (LD), while the receiver is made of a photodiode (PD) and a transimpedance amplifier (TIA).

3.2.2 The random-hole sectorized prototypes

Two GEM detectors with random hole segmentation have been operated in the test beam. One of the two is a rectangular detector and the first random-hole segmented prototype designed in the scope of the CMS GEM R&D. The detector is made of $20 \times 10 \text{ cm}^2$ GEM foils segmented in four rectangular sectors along the larger side; the readout plane is made of 512 parallel strips parallel to the shorter side.

Before the test beam, the $20 \times 10 \text{ cm}^2$ prototype was tested for electrical stability of the GEM foils [58], with no instabilities observed up to a working point corresponding to an effective gain of 2×10^4 . A fine-grain uniformity map of the effective gain with 2 mm pitch has been measured with a ^{55}Fe source moved by a step motor while measuring the anode current on the strips with a picoammeter. The resulting uniformity map (Fig. 3.15) shows a gain loss of about 30% in the sector separation lines with respect to the center of the GEM sector.

The second random-hole segmented detector in the test beam is a full second-generation ME0 detector. Fig. 3.16 shows a picture of the sectorization line crossing the hole pattern; Differently from the $20 \times 10 \text{ cm}^2$, the ME0 has sectorization line not always parallel to the GEM hole pattern; furthermore, since the ME0 azimuthal segmentation is not exactly radial, the readout strips are not parallel to the sectorization lines. For these reasons the efficiency uniformity in the ME0 due to the sectorization is expected to be smaller than the uniformity of the $20 \times 10 \text{ cm}^2$. The comparison of the efficiency uniformity in the two prototypes – as well

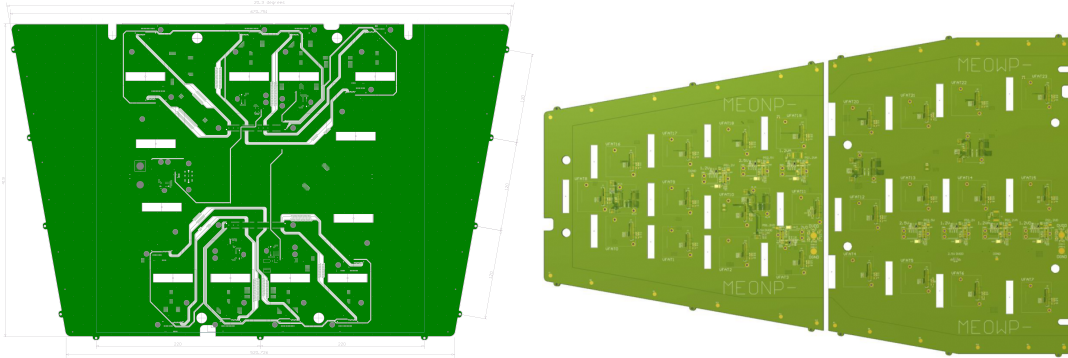


Figure 3.10: Design of the GEBs of the GE2/1 M1 module (top) and of the ME0 narrow and wide (bottom).

as comparison with the efficiency uniformity of the blank-segmented detectors – has been the main measurement performed on the random-hole detectors in the test beam.

3.3 CMS GEM data acquisition software in the test beam

A major goal of the test beam has been testing the final CMS GEM electronics and DAQ software and proving good data-taking quality with particle beams; this section describes the structure of the GEM online software, the COTS back-end electronics used in the data taking and the procedures defined for the calibration and configuration of the on-detector electronics.

3.3.1 Back-end electronics

While the GEM Phase-2 back-end is based on the ATCA standard (X2O board), the test beam has been performed with a commercial back-end board, the CVP-13 (Fig. 3.17), based on the Xilinx VU13P FPGA. The I/O connections used on the board are:

- a PCIe interface allowing to connect the board directly to the motherboard of the DAQ machine, used for the slow control in the DAQ operations;
- four QSFP slots allowing a communication speed up to 25 Gbps per link, used for communication with the OptoHybrid and for local readout;
- a SlimSAS interface used for the external trigger input and for the clock output.

Fig. 3.18 shows the schematic I/O diagram of the CVP-13 in the test beam; a single board can read 8 GE2/1 or ME0 OptoHybrids (i.e. two full GE2/1 or ME0 detectors). The firmware of the back-end board is organized in two blocks sharing a common clock and external trigger, each with two QSFP transceivers reserved; block 0 is used to communicate with the GE2/1 detectors, while block 1 communicates with the ME0 detectors. Two transmitter links in the last QSFP are reserved for the Ethernet-based local readout: the tracking data packets are forwarded through fibers to a NVIDIA Mellanox MCX4121A-XCAT NIC at 10 Gbps. The

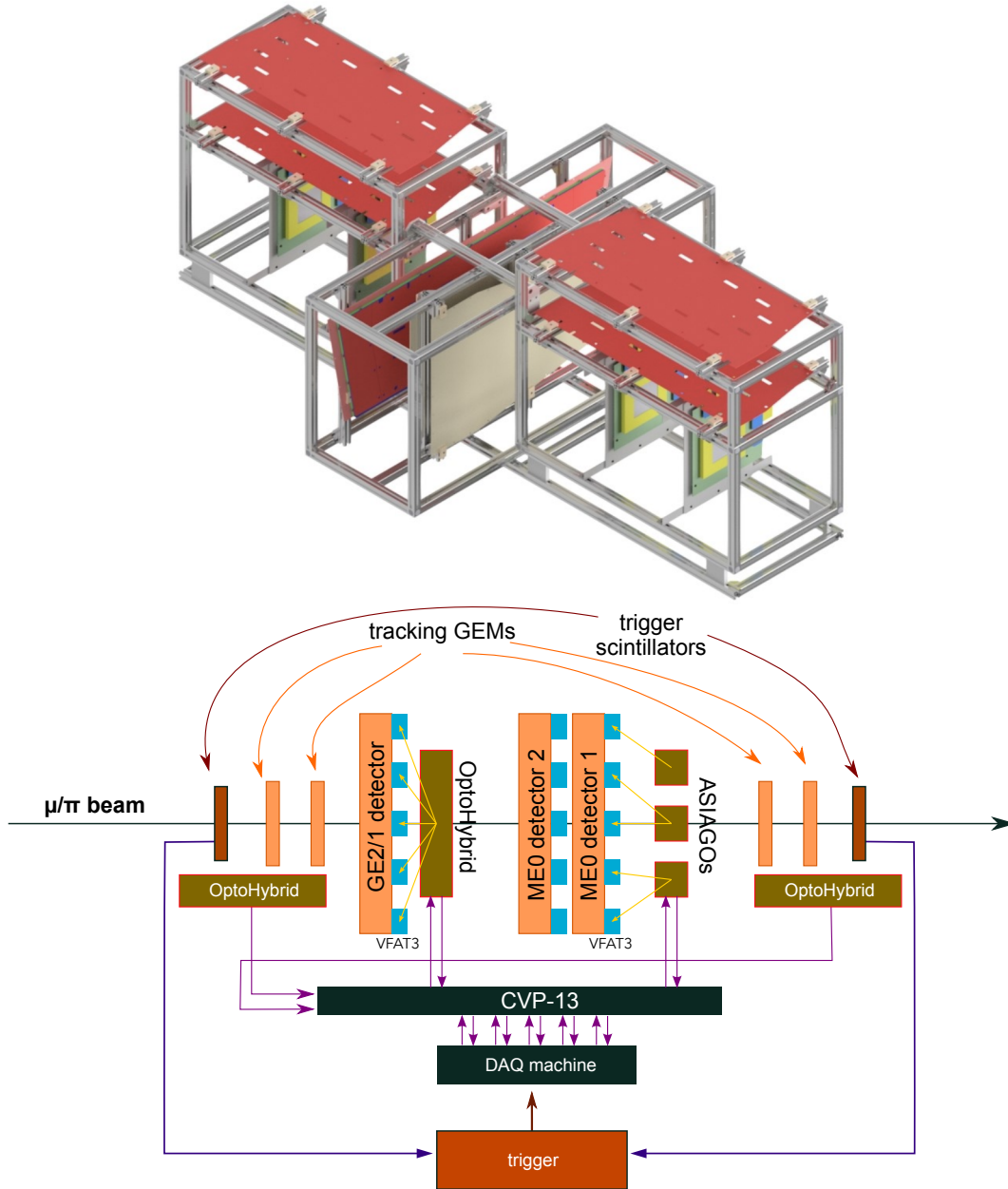


Figure 3.11: Design and layout of the 2021 and 2022 test beam setup. The detectors under test (GE2/1 and ME0) are in the center of the tracker; the GEBs reading out the tracking detectors are mounted on the top of the setup mechanics. The trigger scintillators are not visible in the top drawing.

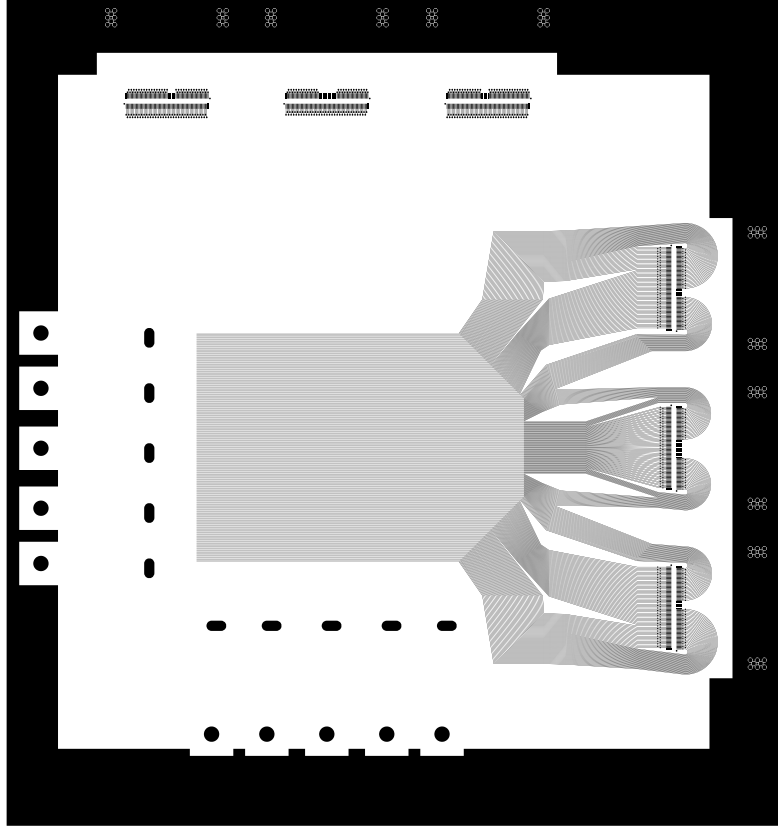


Figure 3.12: Top layer of the read-out board of the tracking detectors.

events from the two firmware block are stored independently and synchronized in the offline analysis.

3.3.2 Data acquisition software

The GEM online software is based on the libraries of the CMS DAQ framework, xDAQ. A block scheme of the composition of the DAQ software is shown in Fig. 3.19. The core part of the data acquisition software is a set of tools that allow the interfacing of the xDAQ applications with the slow control of the back-end board: for each firmware block in the FPGA, a remote procedure call (RPC) server implements high-level DAQ functions (such as the launching of a calibration routine or the configuration of a front-end component) and processes requests from the **AMCManager** applications. The lower-level access to the FPGA registers from the RPC servers and other stand-alone tools is mediated and synchronized by a memory-access layer (**memhub**). The **GEMSupervisor** xDAQ application implements a finite state machine that handles the operations necessary for the data taking (e.g. configuration of the front-end or beginning of a run); a single xDAQ client instance allows the operation of

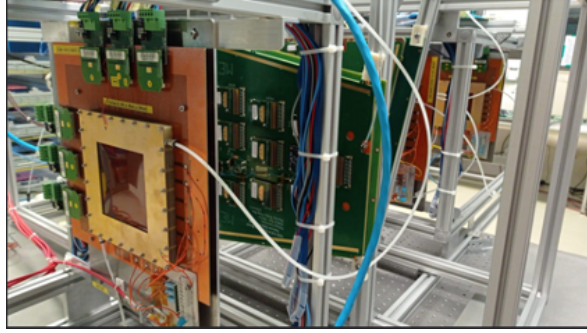


Figure 3.13: Picture of the test beam setup showing one of the tracking detectors.

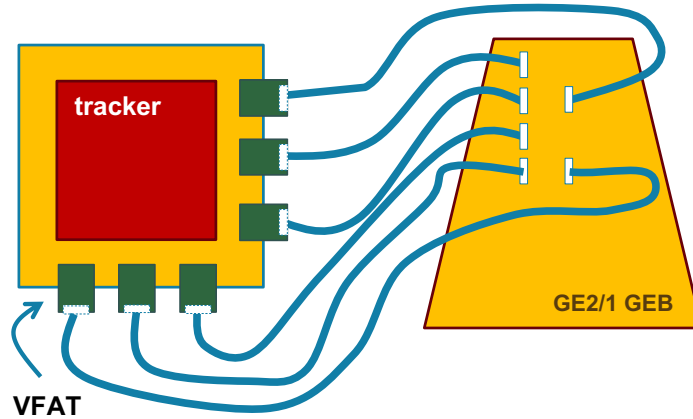


Figure 3.14: Connection scheme between the tracking detector and a GE2/1 GEB with Firefly cables.

the software through a web interface.

3.3.3 Configuration and calibration of the front-end electronics

The set of test and calibration routines allowing the configuration of the detector for data taking are described below. The operation of the detector requires establishing communication with the front-end electronics, calibrating the internal DACs of the VFATs to determine the correct front-end bias, determining the discriminator threshold for an allowed noise rate and setting the optimal latency.

3.3.3.1 GBT phase selection

The eLink between the GBT ASIC and the VFAT3 transmits in separate lines both data and the clock received from the LHC. However, delays in the transmission lines and in the front-end circuits do not ensure that the transmitted signals be always in phase with the clock; for this reasons, the GBT allows shifting the phase of the eLinks with respect to the

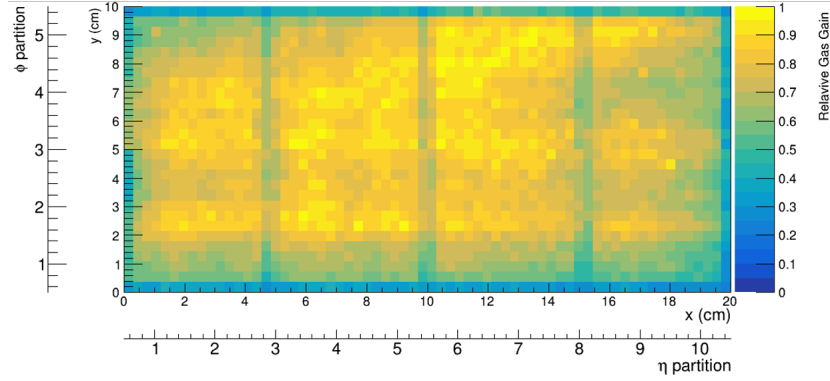


Figure 3.15: Gain uniformity map of the $20 \times 10 \text{ cm}^2$ prototype measured with a movable source. *Result from F. Fallavollita [58].*

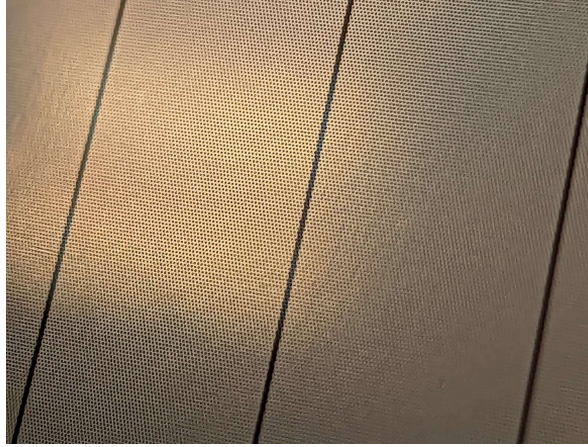


Figure 3.16: Picture of an ME0 GEM foil with random hole segmentation.

clock in a full clock cycle by multiples of 50 ps. A phase alignment routine, the *GBT phase scan*, is performed to choose the optimal eLink phase for each VFAT3 to ensure that the data received by both ends are always sampled in the middle of the opening of the eye diagram.

In a GBT phase scan, for each possible eLink phase a high number of slow-control calls are sent to test registers of the selected VFATs; if at least one call out of 50 yields no response, an error counter for the tested phase is incremented. An example of GBT phase scan result is shown in Fig. 3.20: the optimal phase for each VFAT3 is chosen as the central one in the “good phase window”, i.e. the interval of phases with error count zero. As the eLink phase should depend only on the electrical path between the GBT and the VFAT3 on the GEB, in absence of a proper phase window a default phase can be set based on the statistics of all VFATs in the same position of the GEB for detectors of the same type; however, the GBT phase scan is also a debugging tool since a narrow or absent phase window may point to a communication error due to wrong eLink addressing, fault in the VFAT3 ePort or lack of power from a FEAST.

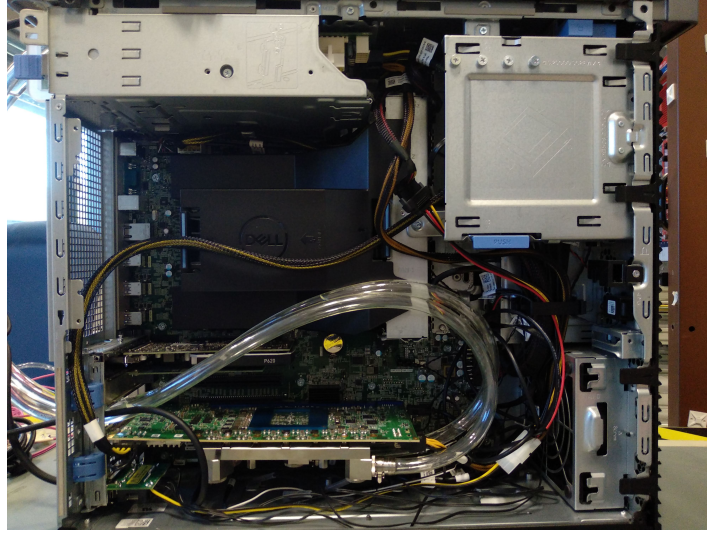


Figure 3.17: Picture of the test beam DAQ machine with the water-cooled CVP-13 in a PCIe slot on the bottom.

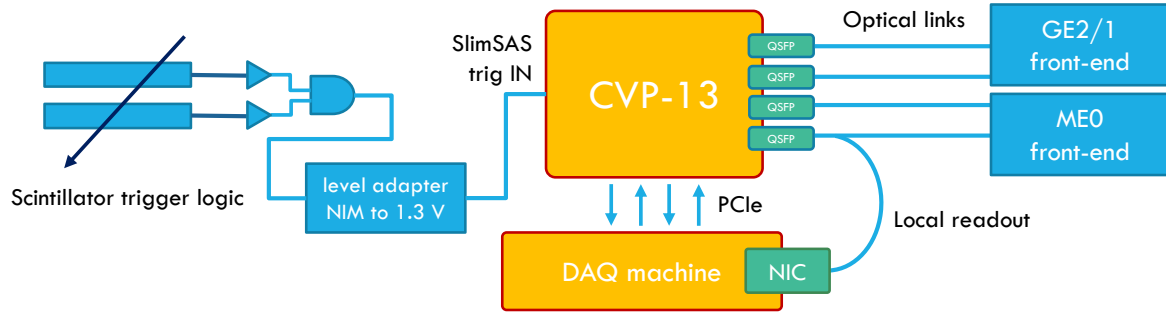


Figure 3.18: I/O scheme of the CVP-13 in the test beam.

3.3.3.2 DAC scan

Each of the VFAT3 front-end circuits have to be biased precisely for compliance with the nominal performance of the chip. Tab. 3.1 lists the bias point of different parts of the analog front-end and their nominal value; the current values are set by voltage sources with a $10\text{ k}\Omega$ input resistor.

Each of the bias variables can be tuned by a dedicated 8-bit or 6-bit digital-to-analog converter (DAC) in the chip; in turn, an ADC allows to read back the set value, in volts or microamperes, corresponding to the chosen value in DAC units. The conversion factor between DAC unit and physical quantity is determined from a *DAC scan*: each DAC is swept between its minimum and maximum value (0 to 63 for the 6-bit registers, 0 to 255 for the 8-bit ones) and the DAC value for the required bias point is determined by interpolation. Fig. 3.21 shows the result on a DAC scan on a VFAT.

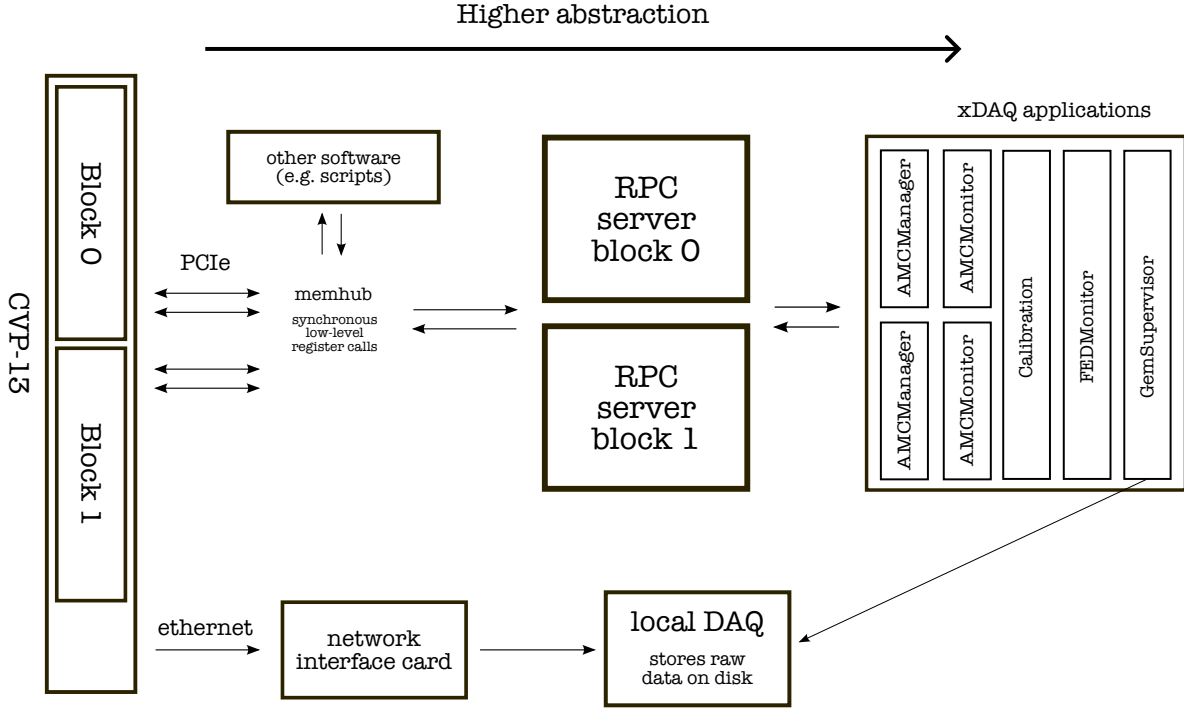


Figure 3.19: Functional diagram of the CMS GEM DAQ used in the test beam.

3.3.3.3 S-scurve scan

The front-end thresholds are set based on the electronic noise, which depends not only on the detector design but also on the grounding scheme of the setup. As the VFAT3 is a digital readout chip, the input charge pedestal cannot be determined by a direct measurement, but is obtained using the charge injection circuit with an *s-curve scan*.

The result of an s-curve on a single VFAT3 channel is shown in Fig. 3.22: the charge injector is configured to generate a sequence of delta-like voltage pulses of increasing charge; for a fixed charge, the ratio between the number of signals over the discriminator threshold and the total number of signals injected is counted. The resulting efficiency trend is fitted with an error function and the *equivalent noise charge* (ENC) of the channel is defined as the sigma of the fit.

Fig. 3.23 shows the result of an s-curve on all the channels of a VFAT; Fig. 3.24 shows a box plot of the channel-by-channel noise level of all the VFATs in a detector. The result of an s-curve is a first strong indication of the expected efficiency of the detector: at the typical effective gain of operation of a GEM detector (of the order of 10^4), the charge per strip induced by a minimum-ionizing particle is expected between 20 and 30 fC. Considering that an effective discriminator threshold on the front-end is a multiple (typically five or six times) of the ENC, the noise measurement has to be taken into account when optimizing the detector configuration. Moreover, the results of an s-curve can help identify dead or detached channels – those not responding to the charge injector or showing too low ENC – or noisy

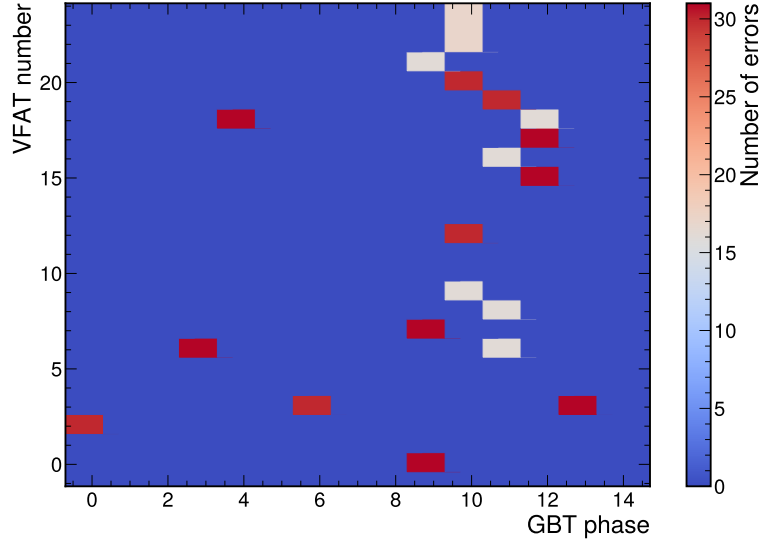


Figure 3.20: Result of a GBT phase scan for the 24 VFATs of an ME0 detector. For each VFAT, the center of the largest blue window – representing the good GBT phases – is chosen as the optimal phase.

DAC	Bias current (μA)	Bias voltage (mV)
Preamplifier bias input transistor	150	1500
Preamp bias leakage compensation	25e-3	0.25
Preamp bias source follower	26	260
Shaper bias folded cascade	26	260
Shaper bias input pair	16	160
Single-differential bias input pair	28	280
Single-differential bias folded cascade	27	270
Single-differential bias source follower	30	300
CFD bias 1	20	200
CFD bias 2	20	200
Preamplifier Vref	/	430 mV

Table 3.1: List of the VFAT3 DACs that can be calibrated with a DAC scan and their nominal bias point.

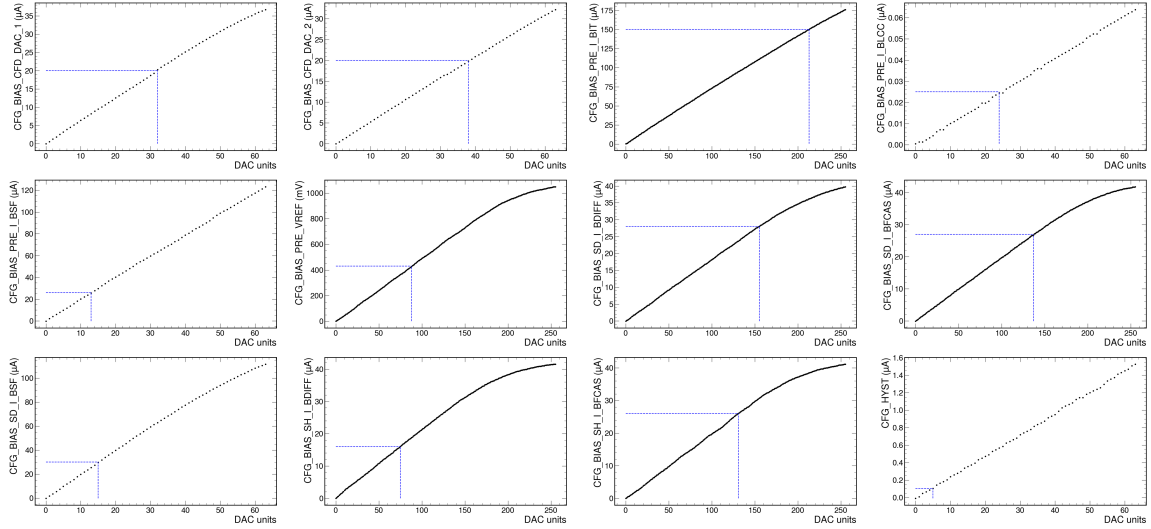


Figure 3.21: Result of a VFAT3 DAC scan, showing for each VFAT register its measured analog value (in μA or mV) as a function of the corresponding DAC value.

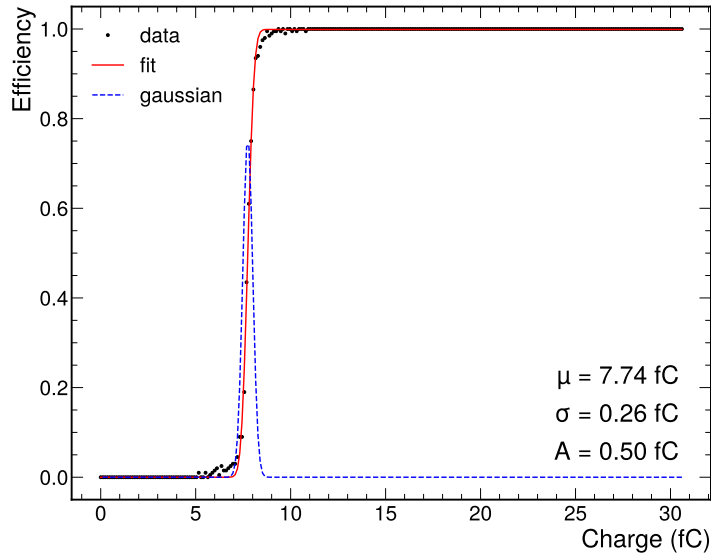


Figure 3.22: S-curve of a single channel in a VFAT3 fitted with an error function. The fit mean corresponds to the discriminator threshold; the sigma corresponds to the ENC of the front-end. A gaussian function with equal mean and sigma is overlapped.

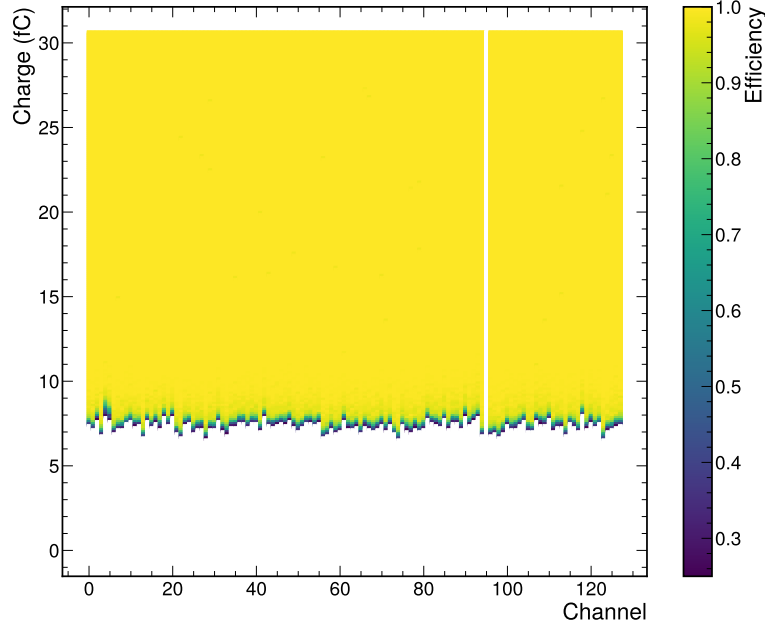


Figure 3.23: S-curve of all channels in a VFAT. The white line corresponding to channel 95 shows a damaged (“dead”) channel.

ones, for example in case of a short circuit between two read-out strips.

3.3.3.4 Comparator threshold

Each VFAT3 has a unique 8-bit DAC to set a threshold on all channels. The exact calibration of the DAC of the comparator threshold varies channel by channel, but on average $q_{\text{THR}} = 0.12 \text{ fC/THR_DAC}$. The comparator threshold is chosen according to the acceptable noise rate; a typical compromise for a noise rate is 100 Hz per VFAT. To determine the threshold, the noise rate on each VFAT3 is measured as a function of the comparator threshold and the chosen threshold value is the minimum value corresponding to a rate lower than the target one.

The measurement is done with the detector HV – or even just the induction gap – turned off to avoid including dark counts or signals from cosmic muons in the rate. There are two fundamental methods for the measurement of the noise rate, from the s-bit path or from the data path. The s-bit path allows the most direct measurement of the signal rate, as the counting data are sent by the VFAT3 to the back-end every time the discriminator fires, without requiring an external trigger; a threshold scan performed by measuring the rate from the s-bit path is called *s-bit rate scan*.

An equivalent method – used in some cases where the s-bit path was not available¹ – consists of counting the signal events in the data path with a cyclic L1A trigger generated by the back-end, after setting the VFAT3 pulse stretch to zero. If n is the number of triggers sent, the total acquisition time is $n \cdot (\text{pulse stretch} + 1) = n \cdot 25 \text{ ns}$; then the average signal rate is:

$$R = \frac{\nu}{n \cdot 25 \text{ ns}}, \quad (3.1)$$

where ν is the number of events in which at least one strip recorded a signal.

Fig. 3.25 on the left shows the result of an s-bit rate scan on a GE2/1 detector: the threshold at 100 Hz is 28 DAC units, corresponding to approximately 3.4 fC. Fig. 3.25 on the right shows an s-bit rate scan taken with the detector high voltage powered on: the steep decrease is interrupted by a plateau at 10 Hz – corresponding to the background of cosmic muons – that vanishes at approximately 200 DAC units or 24 fC, the maximum charge per strip induced by a MIP.

3.3.3.5 Latency scan

The latency is a global VFAT3 parameter that determines the position in the SRAM 1 of the bit that has to be copied to SRAM 2 when the chip receives an L1A; it depends mainly on the signal formation time in the GEM and on the delays in the trigger signal traveling from the trigger logic to the back-end and being distributed to the front-end. The optimal latency for a VFAT3 is the one that maximizes the number of hits received by the front-end when the detector is irradiated by a source synchronous with respect to an external trigger, such as cosmic rays or a muon beam. To determine the optimal latency, the event multiplicity – i.e. the number of events at fixed latency in which at least one strip recorded a signal – is determined as a function of the latency parameter, swept between 0 and 1024 (corresponding to a delay of the trigger up to 25.6 μs) at steps of 1 BX. Fig. 3.26 shows the results of two latency scans performed respectively at pulse stretches zero and three: the optimal latency window has a size equal to the VFAT3 pulse stretch and the latency parameter is set to the center value of the window.

3.3.3.6 DAQ and data taking

The calibration procedure outlined above allows to determine all the parameters required for the configuration of the detector. The data acquisition *per se* consists of a sequence of configuration steps that are executed when the data taking is started:

1. all the TTC (trigger and timing control) generator counters in the back-end are reset and the reception of external triggers is stopped;
2. the optical links to the OptoHybrid are reset;
3. the GBTs are re-configured; the GBTs that do not respond to a connectivity check and the relative VFATs are masked out;

¹For example in the 2021 test beam campaign, in which the tracker VFATs were controlled by cables with no s-bit lines.

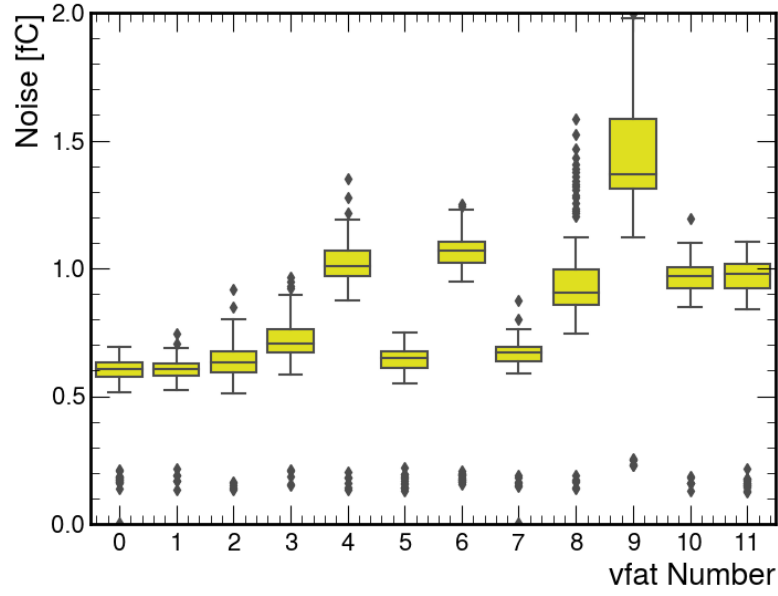


Figure 3.24: Box plot of noise levels of all channels in the 12 VFATs of a tracking detector. The grey dots are outliers.

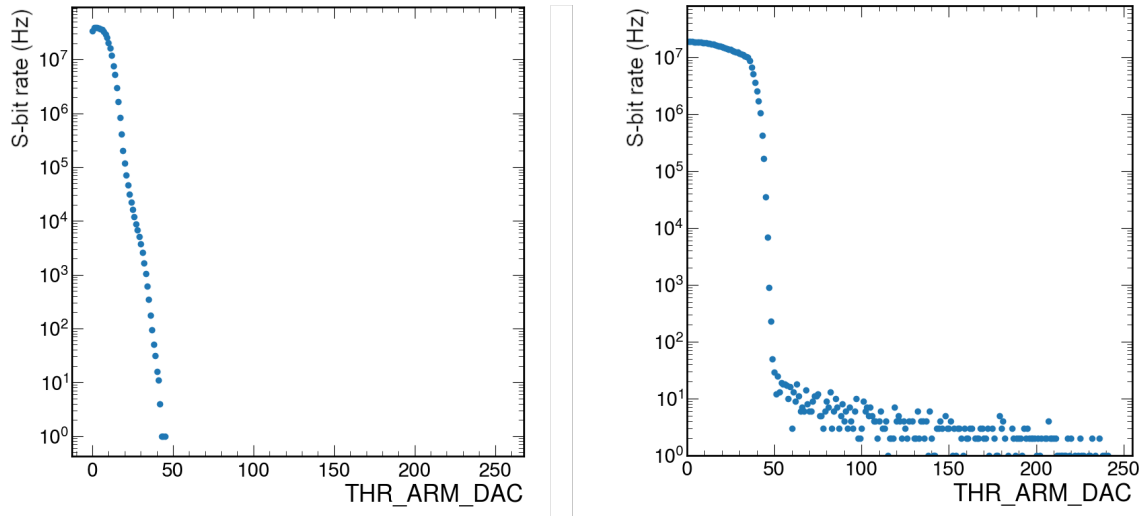


Figure 3.25: S-bit rate scans with the detector amplification off (left) and on (right); the latter shows the plateau due to cosmic muons.

4. the GBT phases determined from the GBT phase scan are written to the front-end;
5. the FPGA of the OptoHybrid, if present, is re-programmed;
6. the VFATs are configured with the DAC parameters (including thresholds and latencies) determined from the detector calibration;
7. a ReSync signal is sent to the VFATs, which empty and re-align their SRAMs;
8. the VFATs are configured for *run mode*, i.e. to transmit data to the back-end after receiving an L1A;
9. the back-end starts accepting external triggers;
10. the local readout is enabled to receive DAQ data.

3.4 Test beam operation

The test beam campaigns have taken place in the North experimental Area at CERN [59]. Served by the CERN Super Proton Synchrotron (SPS), the North Area hosts both physics experiments and test beams (Fig.3.27); in particular, the GEM test beam has taken place in the EHN1 surface hall (shown in the picture in Fig.3.28), in the H4 beam line placed downstream of the T2 target.

The T2 target generates mainly pions and kaons from the primary SPS 400 GeV/c protons; in turn, the secondary beam can produce a muon beam from decay into a secondary target controllable by the line user. The test beam studies described in this thesis were performed with a muon beam; the core of the muon beam has a diameter of 10 cm, while the pion beam has a core diameter of 1 cm. Fig. 3.29 shows a two-dimensional beam profile of the muon and pion beams measured in the test beam with one of the tracking detectors.

The North Area spill structure follows the SPS filling scheme, with spills of approximate 4.8s duration arriving every 30 to 60s, depending on the SPS cycling. The beam intensity is limited – mainly by safety constraints – to about 10^4 per spill.

After the test beam setup installation in the beam area, the electronics front-end is first calibrated. After the proper VFAT3 phases have been determined through a GBT phase scan and the VFATs have been configured by a DAC scan, an s-curve is taken on the detector to check the noise in the grounding configuration. The setup grounding is fixed if necessary and the VFAT3 thresholds are determined by an s-bit rate scan and written to the front-end.

The high voltage of the detectors is turned on following a slow ramp-up procedure called “high voltage training” that consists of biasing each GEM foil at a time at gradual voltage steps and then turning on the gaps between the foils, from the drift to the induction gap, one by one; this procedure lasts a few hours and is needed to limit the probability of spark damage by impurities already present in the detector volume. After all the detectors are powered at nominal bias, a latency scan is run in presence of the beam; the optimal latency is set for each VFAT, after which regular data taking runs can take place.

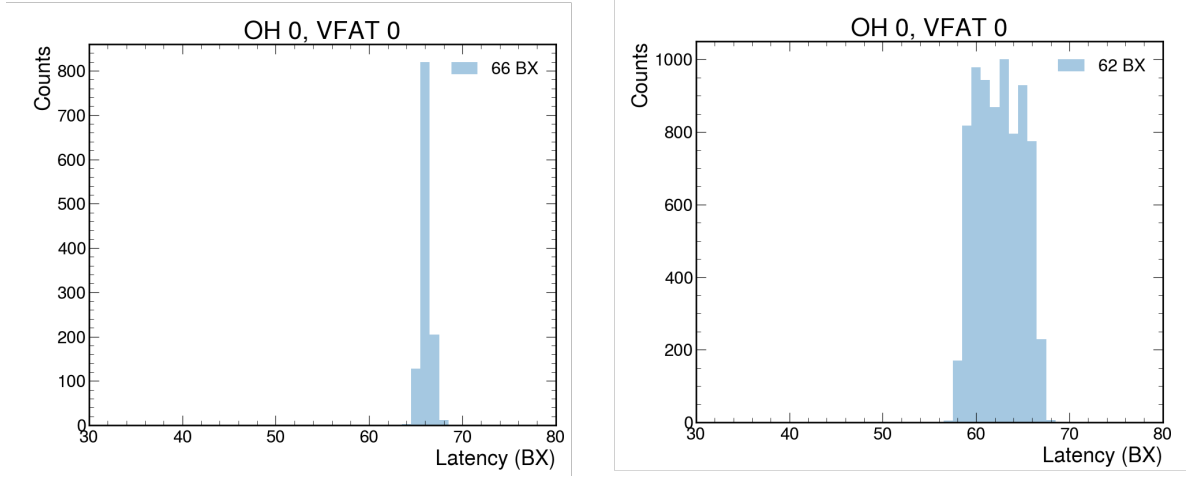


Figure 3.26: Latency scan on two VFATs at pulse stretch 0 (left) and 7 (right).

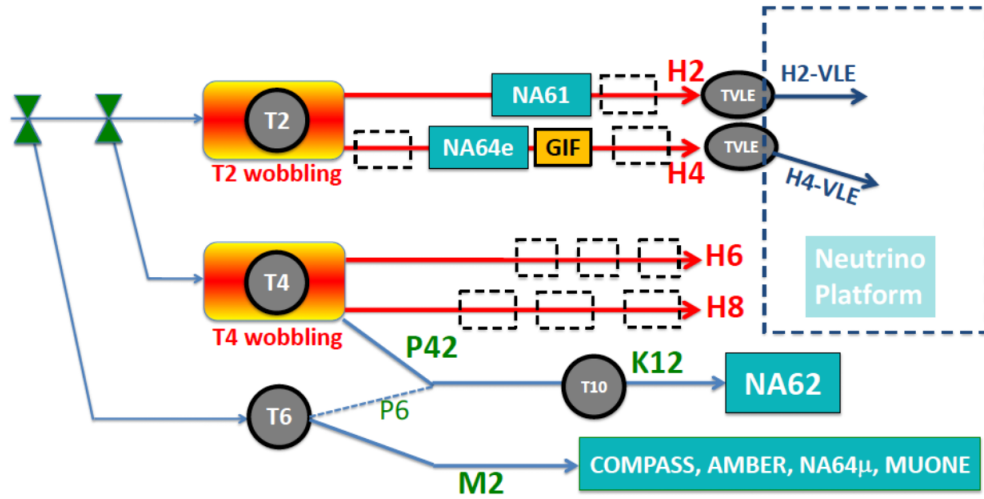


Figure 3.27: Scheme of the beam lines in the North Area served by the SPS [59].



Figure 3.28: Picture of the EHN1 hall, showing the four beam lines and the area occupied by the GEM test beam in red. Adapted from [60].

3.5 Offline reconstruction and analysis

I have developed an offline reconstruction framework for the analysis of the tracking data. The typical reconstruction workflow detailed in the following paragraphs is made of these steps:

1. decoding the raw event data;
2. mapping the front-end channel information to the detector geometry;
3. clustering neighbouring strips in each event to obtain hits;
4. converting the local hit information to global coordinates;
5. fitting a muon track through the hits in the tracking detectors;
6. extrapolating the track to the detectors under test.

The analysis of the reconstructed track data is aimed at performing first a software alignment of the detectors; once the alignment corrections are known the space resolution and efficiency are measured.

3.5.1 Data format and unpacking

The raw event data are stored in a binary format, structured following a lightweight version of the CMS event data format; the first step of the reconstruction, the *unpacking*, reads each event sequentially and stores all events as structured data.

The innermost part of the event data package is the VFAT3 payload, i.e. the data packet transmitted by the VFAT3 to the OptoHybrid after an L1A; Tab. 3.2 shows a simplified version

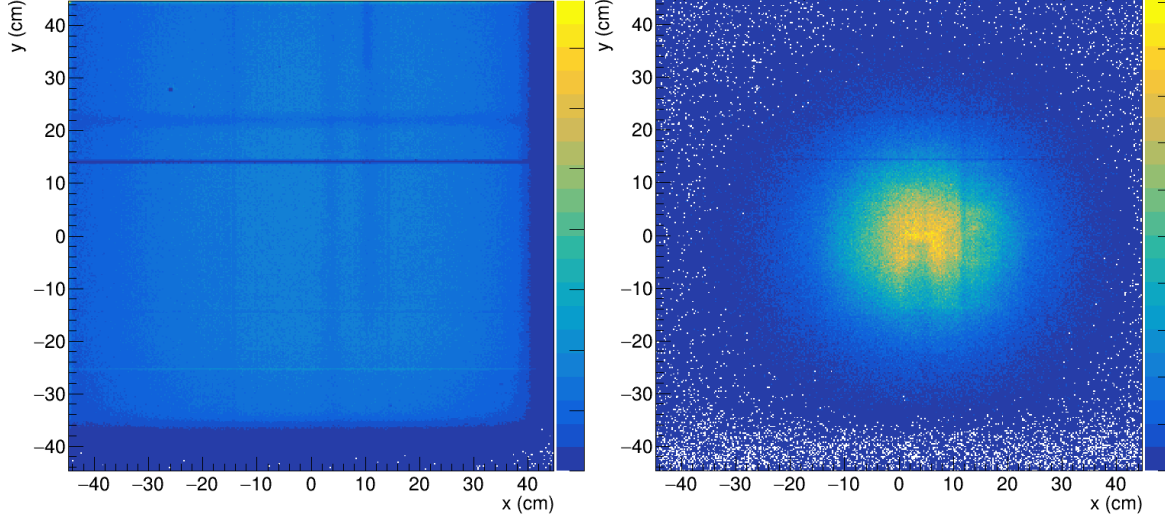


Figure 3.29: Muon (left) and pion (right) beam profiles measured in the test beam with a tracking detector.

of the VFAT3 payload data format containing only the essential information. The VFAT3 payload is made of three words of 8 bytes each; the first six bytes of the first word make a header containing the following metadata:

- the VFAT3 index (position) on the OptoHybrid, to be used to determine the hit position;
- a flag for the presence of a possible error in the cyclic redundancy check (CRC), a checksum computed from the channel data string to detect possible transmission errors such as an unstable phase lock with a GBT;
- the event counter (EC), an 8-bit local counter incremented at reception of each L1A;
- the bunch crossing counter (BC), a 16-bit word incremented at every LHC clock cycle and reset at 3564 (every $89\mu\text{s}$, i.e. the LHC orbit period).

The remaining two bytes of the first word, together with the entire second word and the first six bytes of the third word, make up the hit information on the 128 channels; the final two bytes of the third word are a trailer containing the CRC of the channel data.

	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60
Word 1	Position		CRC flag				EC		BC				Channel data			
Word 2	Channel data															
Word 3	Channel data												CRC			

Table 3.2: Data format of the VFAT3 payload. Each cell represents four bits.

The payloads from different VFATs in one OptoHybrid are grouped together in a *chamber payload*, enclosed by a 8-byte header and trailer (Tab. 3.3). The header contains the number of VFAT3 words in the payload and flags possible errors for event building – such as low space in the back-end FIFO or possible mismatches between the event counter computed locally in the VFATs and the event counter computed in the back-end; the trailer contains a binary mask for the VFATs included in the event and a bit mask for the VFATs that have zero-suppression enabled.

0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60
									VFAT3 count			Error flags			
VFAT3 payload															
VFAT3 count				Zero suppression						VFAT3 mask					

Table 3.3: Data format of the chamber payload.

Finally, different chamber payloads are grouped together in a single *AMC event* stream (Tab. 3.4); the AMC header contains information on the FED number and AMC slot (univocal identifier of the back-end crate and the back-end board number in the CMS DAQ) and on the event counter and bunch counter computed by the back-end, to be compared to the VFAT3 counters for sanity check. Additionally, the AMC header contains the *orbit counter* (OC), which is increased at each LHC orbit period and can be used together with the BC to determine an event timestamp; while in the CMS DAQ such counters are controlled centrally by the LHC and distributed to each detector through the CMS trigger, timing and control infrastructure (TTC), in a standalone setup such as the test beam they are generated internally by the back-end.

0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	
	Slot	EC						BC			Length					
FV	EC			OC MSB				OC LSB				Slot		FED		
Chamber mask						OC MSB						n. chambers				
Chamber payload																
							Run type		Run parameters							
Ethernet CRC												Words in event				

Table 3.4: Data format of the AMC event.

3.5.2 Strip mapping and clustering

For each VFAT, the decoded channel hit data are mapped to the strip number on the detector readout board, then the neighbouring strips in each events are grouped in clusters. The

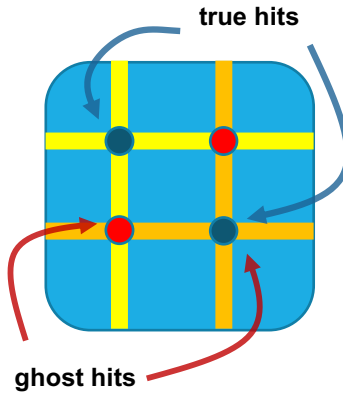


Figure 3.30: Combination of two rechits in each of the two readout plane in a tracking detector showing the two-dimensional properly reconstructed hits and the ghost hits.

clustering algorithm is optimized to work in polynomial time and takes into account the fact that the strip numbers do not appear in order in the raw data. The algorithm works on the list of strips that recorded a hit and it follows these steps for each detector and eta partition. If the position of the first and last strips in a cluster are called $n_{\min}$ and $n_{\max}$, the steps are:

1. the first strip for the chosen chamber and eta partition is removed from the list and used as seed for a cluster of size 1, with $n_{\min} = n_{\max}$;
2. the remaining list is scanned until a strip with position equal to $n_{\min} - 1$ or $n_{\max} + 1$ is found; the strip is removed from the list and added to the cluster and the cluster size is incremented by 1;
3. the list scan restarts from the beginning;
4. steps 2 and 3 are repeated until the end of the list is reached, then a new seed is defined from the first strip of the list;
5. steps from 2 to 4 are repeated until the list is empty.

The reconstructed hits are defined from the clusters using the local detector coordinates; the local x position of the hit is defined as the geometrical center of the cluster and the local y position as the center of the strip along its longitudinal direction. On the tracking detector, reconstructed hits in the two readout planes are combined to define a two-dimensional hit. In presence of multiple hits in each readout plane due to the presence of noise over threshold, background or multiple tracks passing through the detector in the same event, all possible hit combinations are created and stored; this choice gives rise also to ghost hits (Fig. 3.30), which are later rejected based on criteria in the track reconstruction.

3.5.3 Track reconstruction and extrapolation

Once the reconstructed hits are found, the hits in the tracking detectors are fit to a straight line in space to determine the particle trajectory. In events in which each tracking detector contains only one two-dimensional hit, one track is reconstructed and stored. In presence of background hits, the procedure is the following:

- for each possible combination of two-dimensional hits, a track is reconstructed;
- the track with the lowest χ^2 is kept and the others are discarded;
- the reconstructed hits that do not belong to the selected track are discarded.

In absence of a background source, most of the events contain only one possible combination of reconstructed hit, while the background rejection is more relevant for the track-based efficiency measurement performed in the ME0 GIF++ test beam (chapter 4).

The track is extrapolated to the planes of the detectors under test. The two-dimensional position of the extrapolated track is called *propagated hit*.

3.5.4 Alignment

A software alignment of the setup along the transversal direction to the beam axis (x and y) and along the axial angle is performed on the tracking data.

3.5.4.1 Tracker alignment

The tracker alignment is performed first. The transversal alignment is performed iteratively. Each iteration follows these steps (Fig. 3.31):

1. a tracking detector is selected as the detector under test;
2. tracks are built using the other tracking detectors and extrapolated to the detector under test;
3. the residuals between the propagated hit position and the reconstructed hit position are calculated;
4. the transversal alignment corrections along the x and y axis are determined as the average of the residual distribution;
5. steps 1 to 4 are repeated for all the other tracking detectors.

The procedure is iterated for all tracking detectors until the iterative corrections become negligible. Fig. 3.32 shows the alignment converges after five iterations.

The angular alignment of the tracker is an iterative procedure as well, with iterative steps similar to the transversal alignment; in this case, the iterative correction can be determined

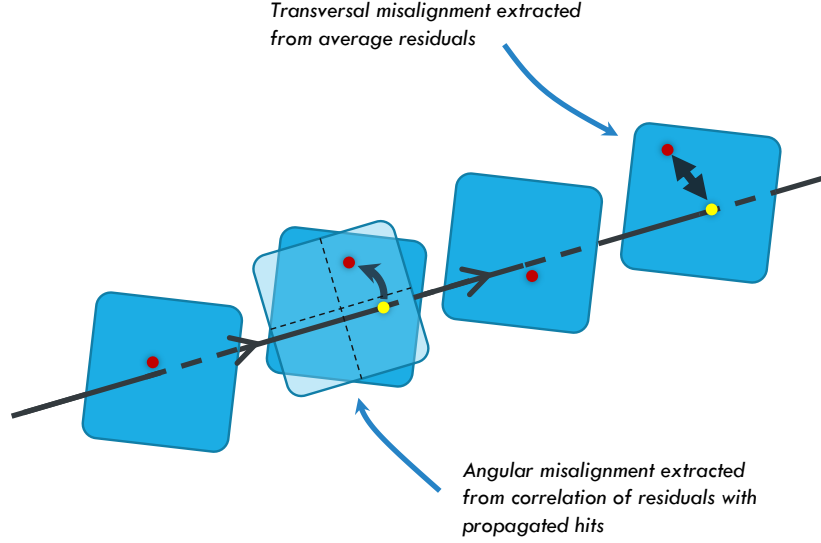


Figure 3.31: Steps for the alignment of the tracker detectors.

by treating it as a parameter in the change of coordinates between the propagated and reconstructed hit positions:

$$\begin{cases} x_{\text{residual}} = x_{\text{reco}} - x_{\text{prop}} = x_{\text{prop}}(\cos \theta - 1) - y_{\text{prop}} \sin \theta \\ y_{\text{residual}} = y_{\text{reco}} - y_{\text{prop}} = x_{\text{prop}} \sin \theta - y_{\text{prop}}(\cos \theta - 1) \end{cases} \quad (3.2)$$

Therefore the correction θ can be obtained from the correlation between the propagated hit position and the hit residuals. In particular, since $(\cos \theta - 1) \sim \theta^2$ while $\sin \theta \sim \theta$, the best precision is obtained by using the correlation between the x residual and the y propagated hit position (or vice versa). Fig. 3.33a shows the measurement of the angular correction of a tracking detector, while Fig. 3.33b shows the iterative corrections converging after six steps.

3.5.4.2 Alignment of the CMS detectors

The information given by the residuals is not sufficient for the alignment of the CMS detectors under test because of the large uncertainty on the η coordinate. Therefore, the corrections in the vertical and angular coordinates are obtained from the events where two neighbouring eta partitions have recorded a hit. In such events, the propagated hits on the detector cluster around the separation line between two eta partitions, as shown in Fig. 3.34 on the left; the background (Fig. 3.34 on the right) is made of noise, background hits or events in which two uncorrelated tracks hit the detector in the same event. With the two-eta requirement, a linear fit of the distribution of the propagated hits (Fig. 3.34) allows extracting the y correction from the line offset and the θ correction from the slope. After the vertical and angular alignment have been performed, the horizontal alignment correction can be determined simply from the average residual in the x direction.

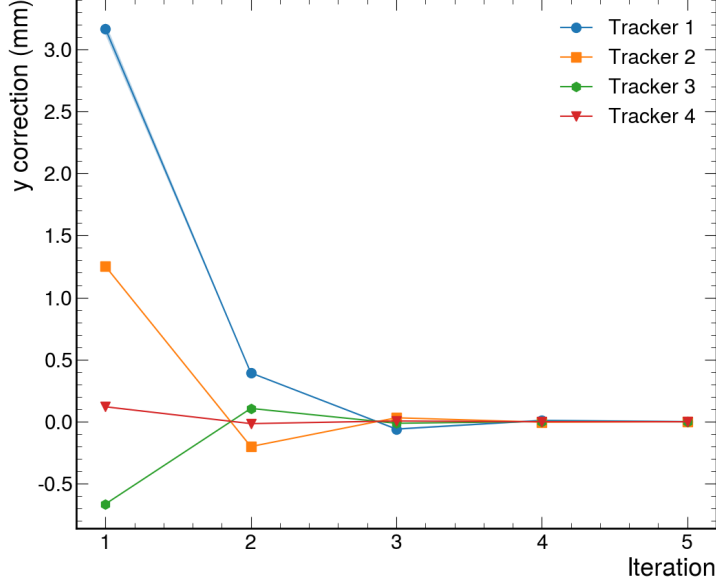


Figure 3.32: Iterative transversal alignment corrections in the y direction for all detectors in the tracker.

3.6 Test beam results

3.6.1 Tracker performance

An efficiency turn-on curve of the tracking detectors is taken to determine the optimal working point. The efficiency is measured using tracking information to reject background hits and is defined as:

$$\epsilon = \frac{\text{number of events with a hit matching a track}}{\text{number of events with a track passing in the detector}}; \quad (3.3)$$

a hit is qualified as “matching” if it lies within a distance from the propagated hit lower than 3.5 times the standard deviation of the residual distribution.

Fig. 3.35 shows the result of the high-voltage scan. The x-axis is expressed in *equivalent divider current*, i.e. the current that flows in the high-voltage divider used to power the detectors. All the detectors reach an efficiency plateau; however, the efficiency at plateau of the tracking detectors 3 and 4 is lower than 95% – while the first two reach an efficiency of 98% – due to the lower gain at equal working point. This is confirmed by the average cluster size in both readout planes, which is also lower for detectors 3 and 4 (Fig. 3.36).

The overall low efficiency in the tracking detectors is related to the high thresholds in the readout electronics. Fig. 3.37 shows an example of the noise in the front-end electronics measured with s-curves, comparing a tracking detector (left) with the GE2/1 detector (right): the noise in the tracker can reach up to 1.25 fC, while the noise on the GE2/1 is always lower

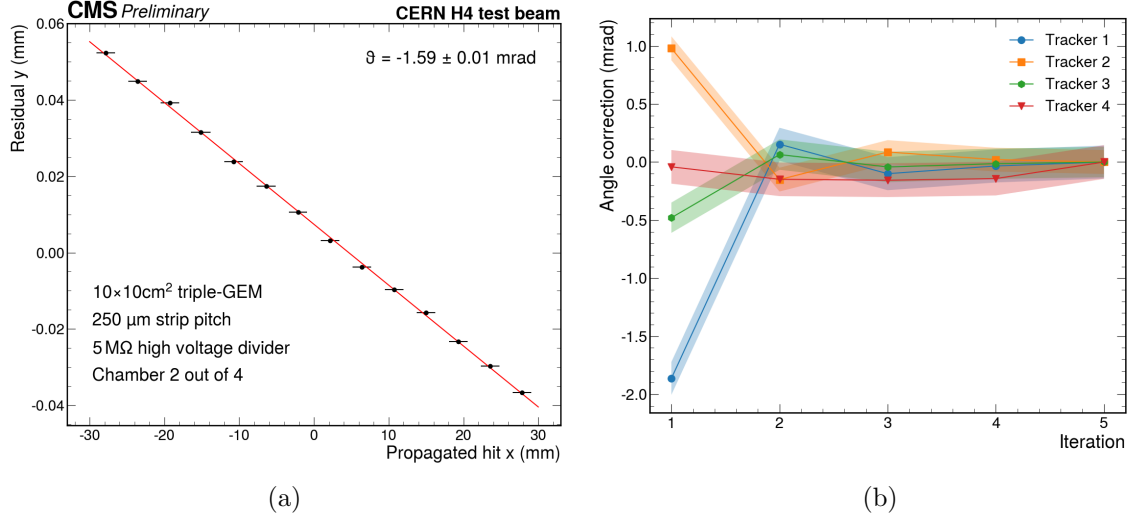


Figure 3.33: (a) Angular alignment correction on tracking detector extracted from residual correlation with propagated hits. (b) Iterative angular alignment corrections for all the detectors in the tracker.

than 0.5 fC . There are three main reasons for the large difference in the electronic noise of the two detectors:

- the presence of the GEB in the GE2/1 and ME0, which acts as a shielding and grounding plane for the readout board;
- the use of the VFAT3 plugin cards on the GE2/1 and ME0, in place of the VFAT3 hybrids used in the tracker; the input connector of the plugin cards (Hirose 140) has one grounding pin every 10 signal pins, while the hybrid connector (Panasonic 130) has two grounding pins only, at the beginning and at the end;
- in the tracking detectors, the grounding pins of the Panasonic 130 connector were not properly connected to the ground of the readout PCB.

The space resolution of the tracking detectors is measured from the residual distribution; Fig. 3.38 on the left shows the residual distribution along the x directions for the second tracking detector²; the measured space resolution is obtained as the sigma of a gaussian fit to the residuals and is $81.3 \pm 0.3 \text{ } \mu\text{m}$ in the x direction and $81.0 \pm 0.4 \text{ } \mu\text{m}$ in the y direction, larger than the expected value of $250 \text{ } \mu\text{m} / \sqrt{12} = 72.2 \text{ } \mu\text{m}$.

An explanation for the higher observed space resolution is shown in the measured space resolution trend as a function of the cluster size (Fig. 3.38 on the right): the space resolution improves with the cluster size up to cluster sizes 6 and 7, where it reaches a value compatible with the expected resolution; at high cluster size, the space resolution becomes higher than

²The trend is similar for the residual distribution along the y direction.

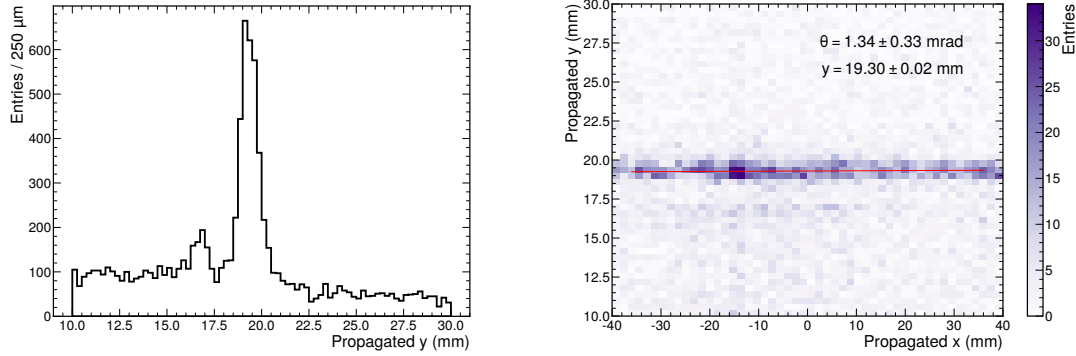


Figure 3.34: Propagated hit distributions of events with reconstructed hits in multiple eta partitions on the GE2/1 detectors, used to align the GE2/1 detector. On the left, projection along the y axis showing the peak corresponding to the eta partition separation. On the right, distribution of the propagated hits in the selected events, showing the separation line between readout partitions. The linear fit (red line) is used to determine the angular and vertical alignment.

100 μm due to delta rays in the avalanche that make the charge spreading asymmetric. The space resolution is also observed to get worse at low cluster size as an effect of the low efficiency, since the signal induced on the external strips in the avalanche is lower in amplitude and can fall below the front-end threshold, biasing the position of the center of the cluster. This behaviour can be changed by a redesign of the readout plane to allow redundant grounding pins.

3.6.2 Phase-2 GEM detector performance

The residual distribution of the ME0 detector measured with muons is shown in Fig. 3.39 and the central peak is fitted with a gaussian function; the space resolution – measured as the sigma of the gaussian fit in local radial coordinates – is $235.05 \pm 2.21 \mu\text{rad}$; this is within the TDR requirements for ME0, as well as better than the space resolution of strip pitch/ $\sqrt{12}$ expected for digital readout. The long tails of the residual distribution are explained by the residual distributions for different cluster sizes (Fig. 3.40): at cluster size larger than three the residuals distribution are wider due to the emission of delta rays that bias widen the clusters, thus biasing the position of the central strip.

A second measurement of the point space resolution is obtained by the “horn” plot of Fig. 3.41: the left plots are the distributions restricted to a range of 10 strips of the position – in strip units – of the propagated hits for events in which the detector records a hit for cluster size; the information on the reconstructed hit position is not used. All distributions show periodic peaks: for even cluster size the peaks are centered on integer strip positions, while they are centered on half-integer positions for odd cluster sizes. The geometrical interpretation – assuming the tracks are perpendicular to the detector surface – is that the parity of the

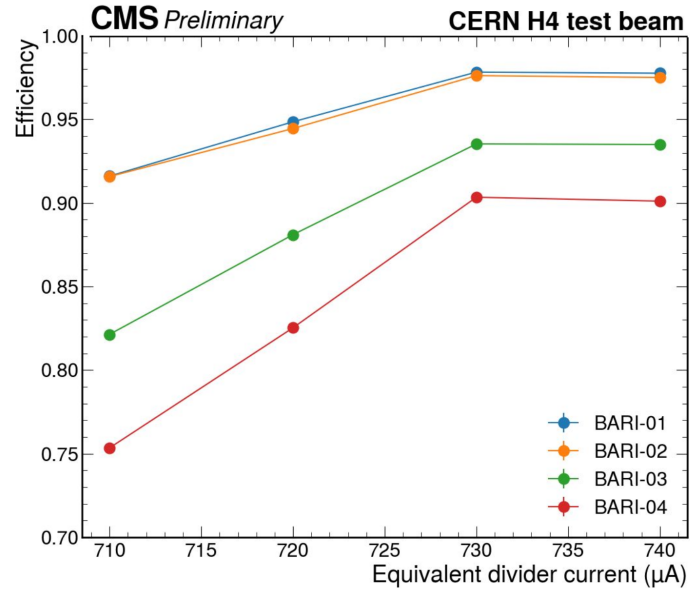


Figure 3.35: Efficiency turn-on curve of the tracking detectors.

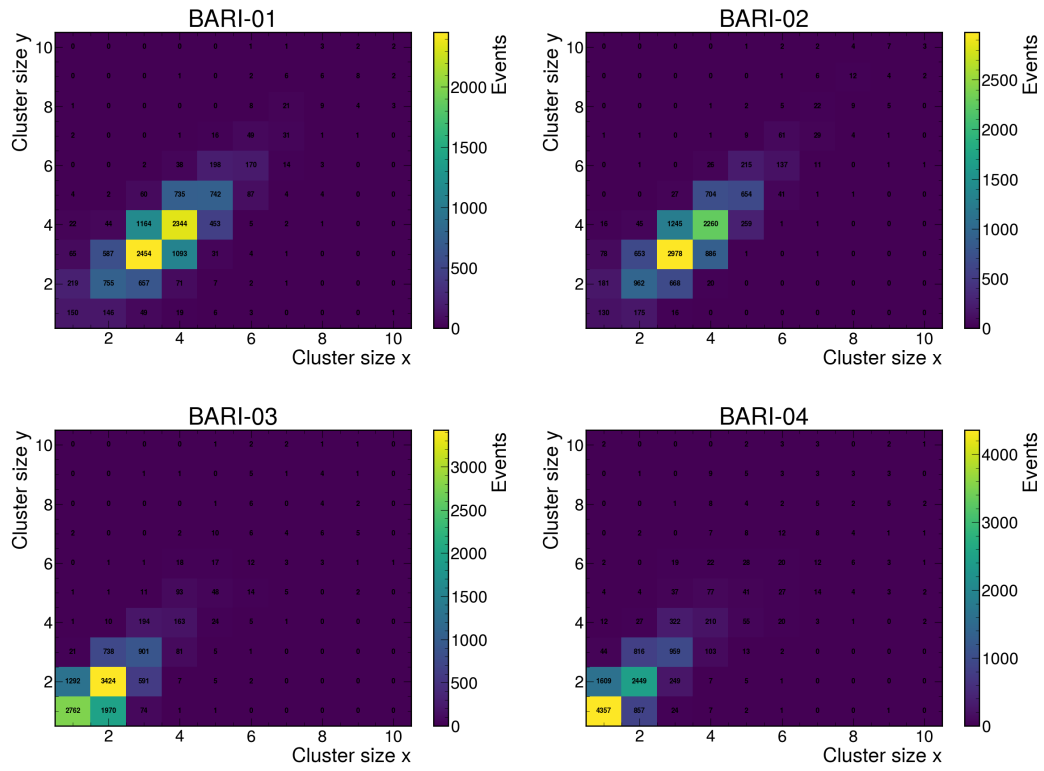


Figure 3.36: Cluster size distribution in both read-out planes of the four tracking detectors.

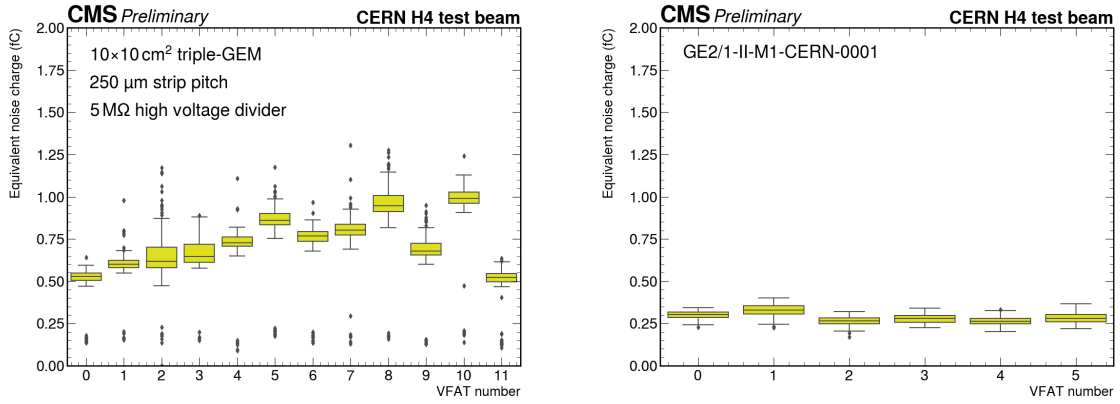


Figure 3.37: Noise levels measured with s-curves of the tracking detector 2 (left) and of the GE2/1 detector (right).

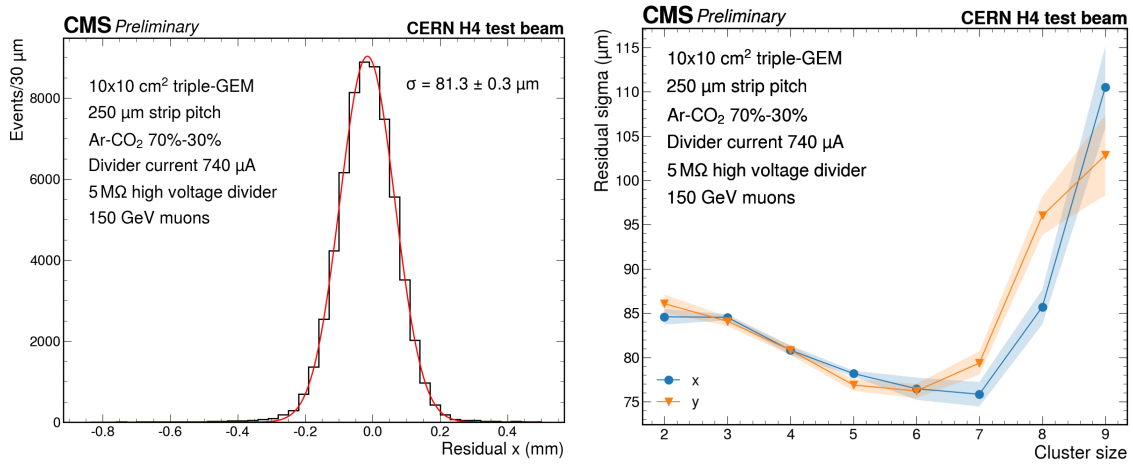


Figure 3.38: On the left, residual distribution in the tracker 2 on the x and y readout planes. On the right, trend of the measured space resolution of the tracking detector 2 as a function of the cluster size.

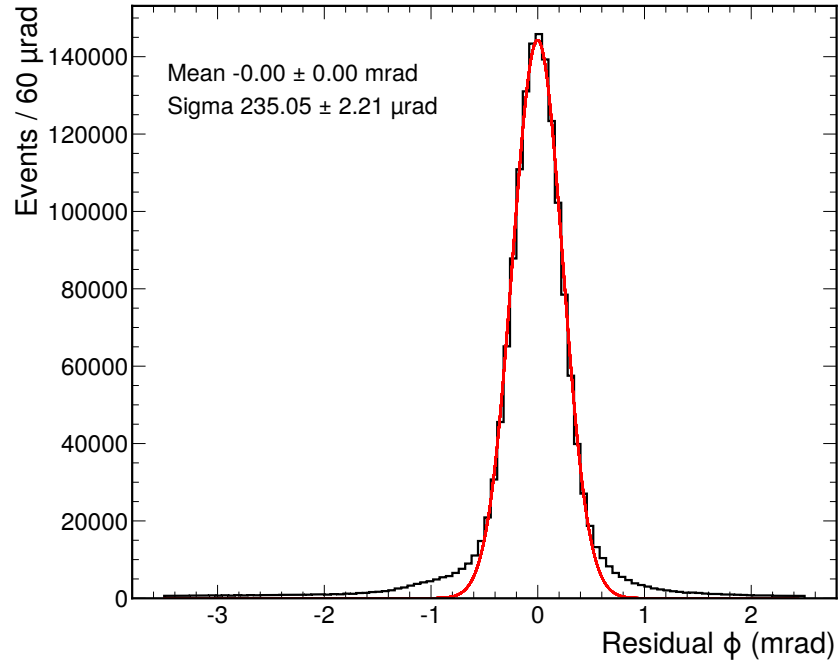


Figure 3.39: Residual distribution of the ME0 detector.

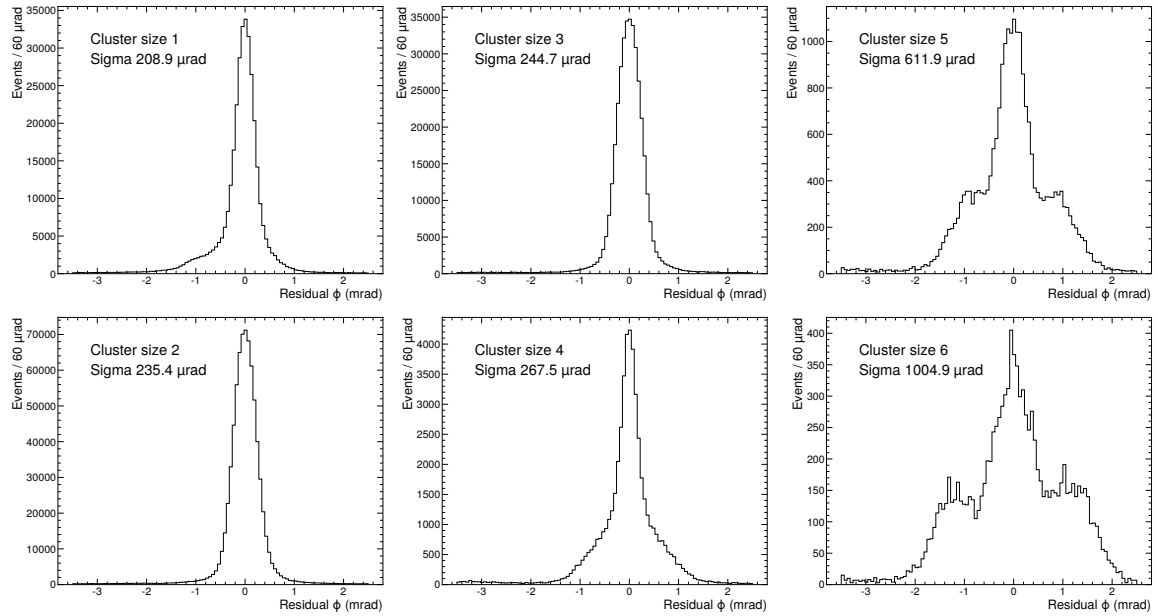


Figure 3.40: Residual distribution of the ME0 detector for different cluster sizes.

	Efficiency	Active area
GE2/1	$98.17 \pm 0.04\%$	99%
ME0 blank	$94.82 \pm 0.06\%$	94%
ME0 random hole	$97.48 \pm 0.04\%$	94%

Table 3.5: Comparison between the efficiency and the dead areas of the three detectors.

cluster size is determined by the position in which the track hits the detector readout plane; the charge sharing in the readout is determined by the position of the avalanche entering the induction gap.

The right-hand side plots in Fig. 3.41 show the distributions of all the propagated hits within one strip; the width of the peak becomes less resolved with higher cluster size, confirming that the space resolution worsens at increasing cluster sizes.

A high-granularity efficiency map of the detector is obtained by binning the propagated hit position by a few hundreds of μm ; Fig. 3.42 (left) shows the efficiency map of the GE2/1 detector. The efficiency to muons is locally close to 1 on a large part of the active area; a few dips in the efficiency profile point to the separation between the GEM foil sectors. Fig. 3.42 (right) shows the efficiency profile obtained by integrating the efficiency map along the x direction; a fit with a gaussian comb shows the efficiency dips lie between 50% and 90%, while the width of the dips – measured as the sigma of each gaussian – is between 186 and 231 μm , in agreement with the width of the dead area created by the segmentation.

The efficiency map of the ME0 detector with the narrow GEB irradiated is shown in Fig. 3.43 on the left. The map shows the profile of the azimuthal GEM foil sectorization and a pillar on the top right region; a slice of the efficiency profile cut along the y axis (Fig. 3.43 on the right) shows the efficiency dips in the sectorization line have a similar width as in the GE2/1 detector but are smaller in depth. The efficiency map of the $20 \times 20 \text{ cm}^2$ random-hole segmented prototype (Fig. 3.44), instead, shows a very limited efficiency loss in the sectorization line, with an efficiency dip of only 4%; nonetheless the width of the dead area is larger with respect to the blank-sectorized detectors, with a sigma of $428 \pm 6 \mu\text{m}$ – presumably due to the angle between the segmentation pattern and the readout strips.

Fig. 3.45 compares the efficiency map of the blank-segmented ME0 and the random-hole segmented ME0 with the entire wide GEB irradiated, showing the lower efficiency loss in the random-hole; the sliced efficiency profiles in Fig. 3.46 show the efficiency loss in the blank-segmented detector reaches up to 80%, while the loss in the random-segmented prototype is limited to about half as much.

The average efficiencies of the three CMS detectors are listed in Tab. 3.5 and compared with the detector active area, coarsely calculated as the ratio between the total detector surface and the area occupied by the sectorization lines. In the case of the two detectors with blank segmentation, the average efficiency and dead area are in agreement within 1%, proving that the reduction of average efficiency below 100% (value closely approached inside a foil sector) is mainly due to the sectorization dead area. The random-hole segmented ME0, instead, has an average efficiency higher than its active surface, showing the effectiveness of the random-hole manufacturing for recovering the efficiency in the sector separation.

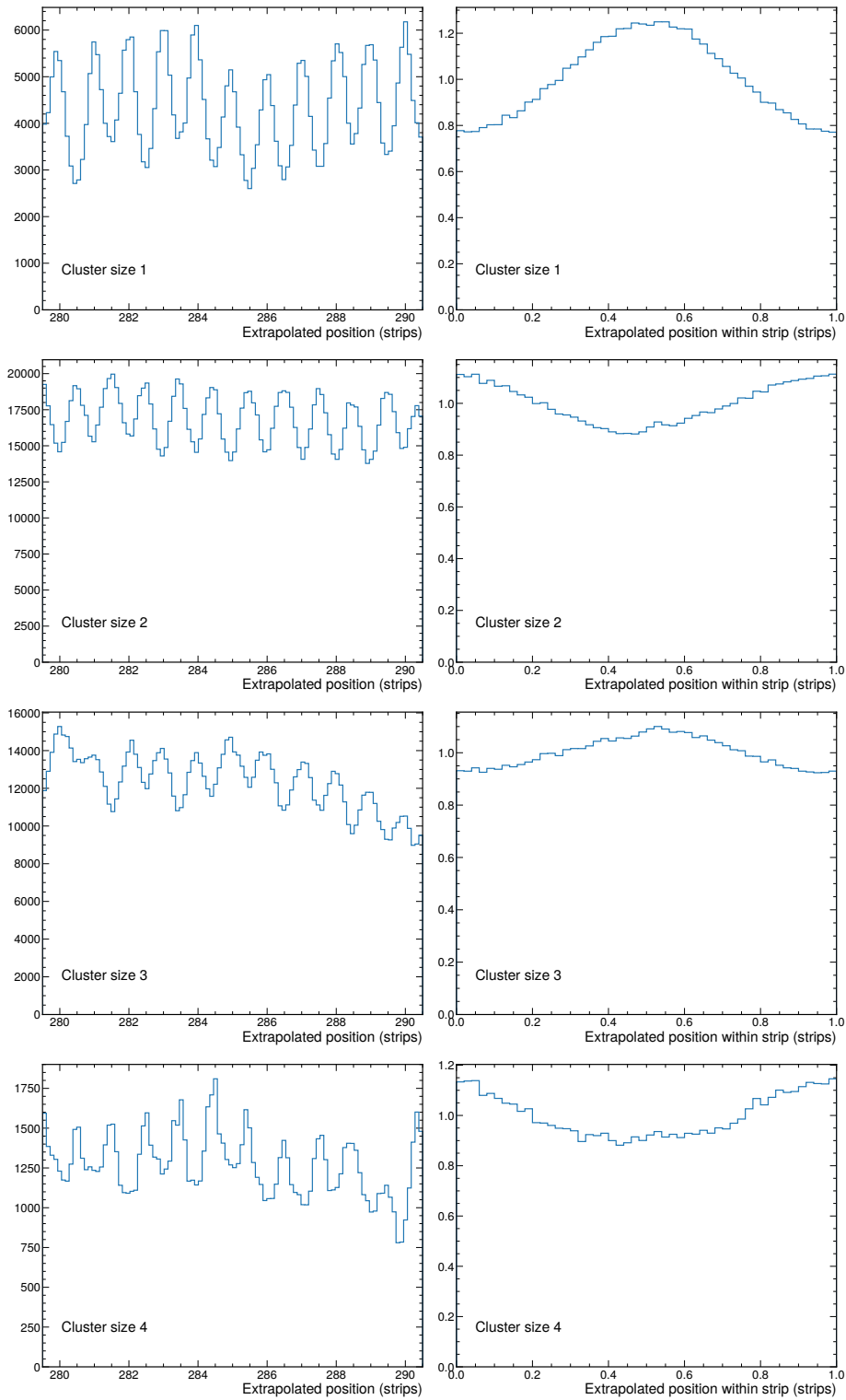


Figure 3.41: On the left, distribution of the propagated hit positions in the GE2/1 – in strip units – for events containing reconstructed hits in the GE2/1 with a fixed cluster size. On the right, distribution of the propagated position of propagated hits within a strip with the same selection.

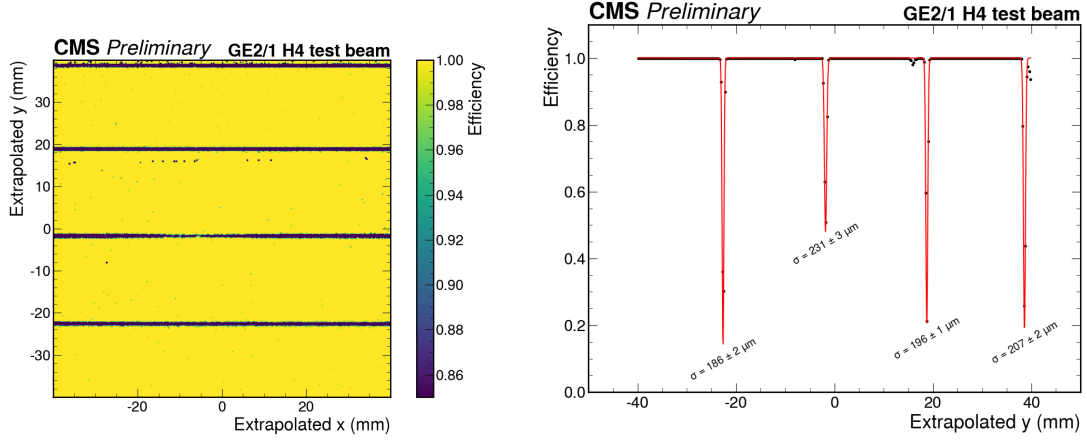


Figure 3.42: (Left) efficiency map of the GE2/1 detector. (Right) efficiency profile along the y axis of the GE2/1 detector.

3.7 Conclusions

The triple-GEM detectors for the Phase-2 CMS upgrade have been tested with muon beams in the CERN North Area in two test beam campaigns. The main goal of the test beam was to demonstrate the performance of the detectors and their final front-end electronics and DAQ with a high-rate beam.

The present chapter has described in detail the final design of the GE2/1 detector, the near-final design of the ME0 detector and the operation of its readout electronics; in particular, the steps needed for the calibration and configuration of the front-end have been described in detail. A reconstruction framework has been developed for a track-based analysis of the test beam data; an offline alignment procedure has been defined for the tracking chambers and for the CMS detectors.

The performance of the tracker has been measured with an efficiency scan as a function of the detectors HV point and a space resolution measurement; the four detectors have a low plateau efficiency, between 90% and 97%, due to the high front-end thresholds, which in turn were related to the sub-optimal design of the readout board grounding. The average space resolution of the tracking detectors (close to $81 \mu\text{m}$) was slightly higher than the expected value (of $72.2 \mu\text{m}$, equal to strip pitch/ $\sqrt{12}$); the discrepancy is found to be due to the dependency of the space resolution on the measured cluster size, which degrades both at low and high cluster sizes.

The performance of the CMS detectors has been measured with the high-resolution tracker; the space resolution is in line with the expected value and confirms the Phase-2 detectors are compliant with the technical design report (TDR) requirement of the order of $100 \mu\text{rad}$.

The efficiency uniformity of the detectors was measured with high statistics in high granularity; the resulting efficiency is locally very close to 1 – also due to the optimized grounding, that allows reaching an excellent signal-to-noise ratio –, with most of the efficiency drops

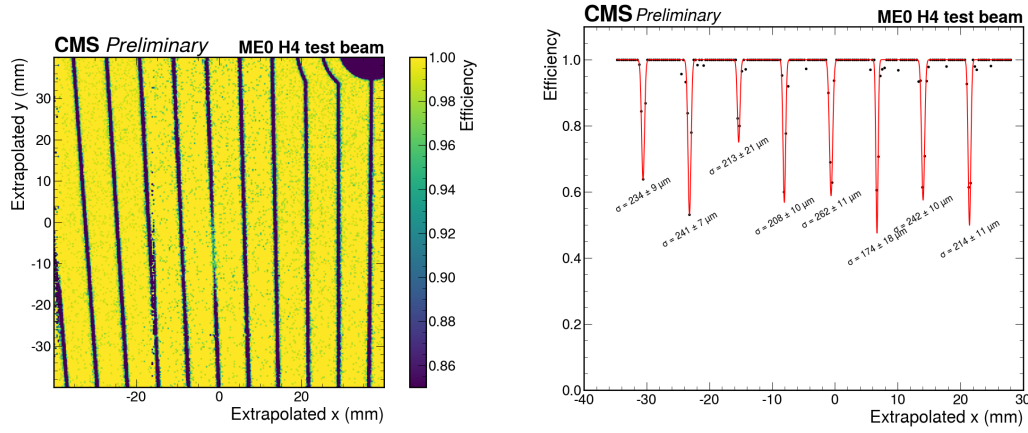


Figure 3.43: Efficiency map (left) and slice along the y axis (right) of the ME0 detector.

localized close to the separation between GEM foil sectors. In this sense, the detector performance exceeds the TDR expectations, since the average efficiency measured over all the detector is lower than 99% only because of the reduced acceptance due to the segmentation.

The decrease in average uniformity is more important in ME0, due to its higher number of sectors with respect to GE2/1. A proposed solution to recover the efficiency loss due to the segmentation is the random hole segmentation; the test beam included two random-hole segmented detectors (a $20 \times 10 \text{ cm}^2$ prototype and an ME0 detector) for performance comparison. The efficiency loss due to the segmentation in the random-hole prototype is lower by about 50% with respect to the blank-segmented detectors, making it an attractive choice for the ME0 GEM foil manufacturing.

The test beam has proven the first successful integration of the GE2/1 and ME0 detector, their front-end electronics and DAQ with a particle beam; the overall detector performance is in agreement with the TDR requirement. Specifically for ME0, a next step of the detector validation would be its operation in high particle rates, which is the main topic of the next chapter.

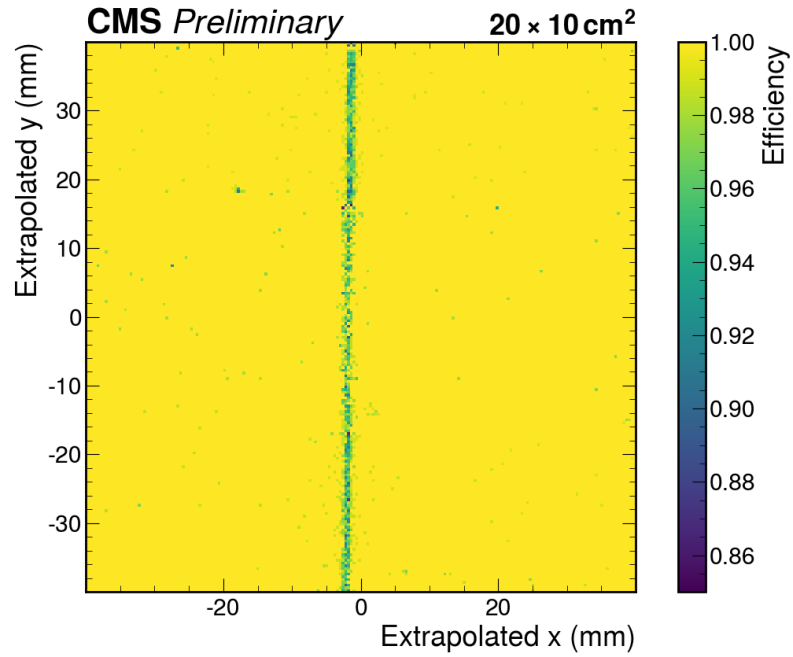


Figure 3.44: Efficiency map of the 20×10 cm² random-hole segmented prototype.

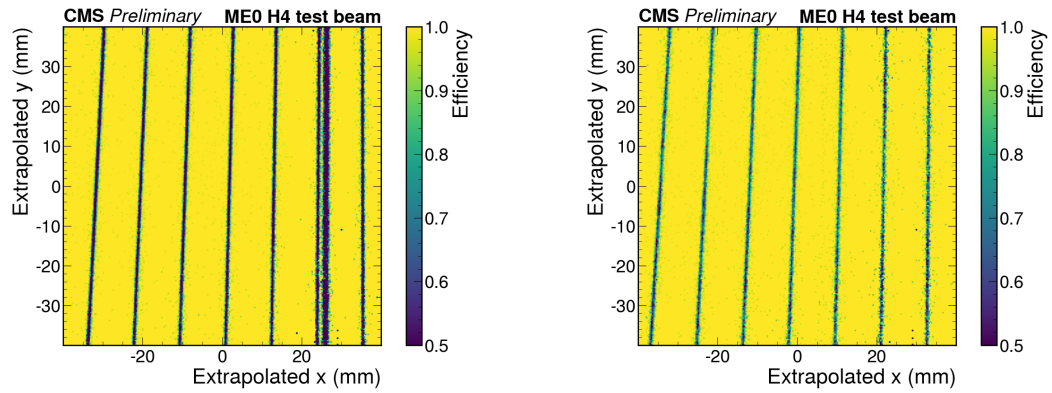


Figure 3.45: Efficiency maps of the wide side of the ME0 blank segmented (left) and random-hole segmented (right).

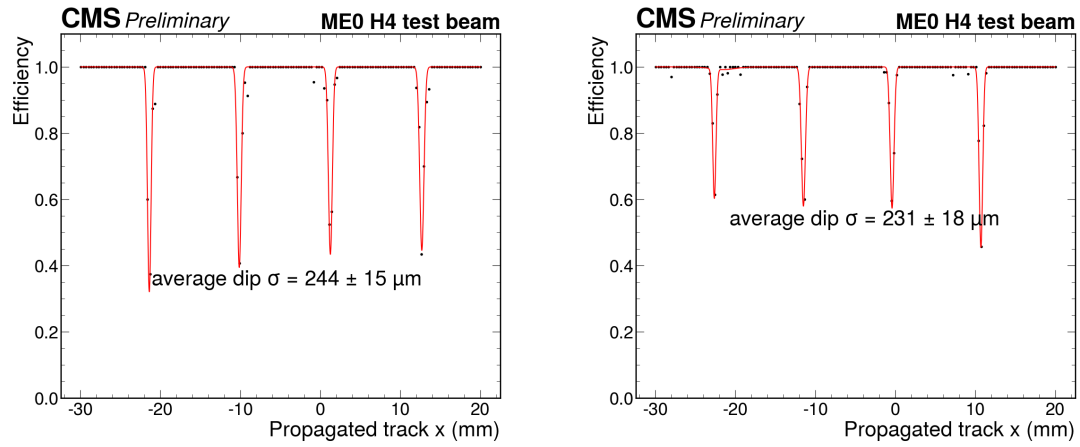


Figure 3.46: Efficiency profiles of the wide side of the ME0 blank segmented (left) and random-hole segmented (right).

Chapter 4

GEM detectors for high-rate environment in CMS: the ME0 station

The present chapter summarizes the optimization of the ME0 detector for the high-rate environment expected in HL-LHC. After a discussion on the expected background environment in ME0 during the CMS Phase-2 operations, the measurements of the rate capability on state-of-the-art large-area triple-GEM detectors are presented. The results of such measurements require a redesign of the GEM foil layout for ME0, which is tested in laboratory and at the GIF++ facility at CERN. Finally, the new detector design is validated in a high-background test beam with final electronics.

In the last section the results of the final design are again related to the operating conditions expected in Phase-2, this time taking into account both the effects of the detector and of the front-end electronics on the rate capability.

4.1 Expected background environment in the ME0 detector

In the GE1/1 and GE2/1 stations, the expected fluxes of background radiation are between 1 and 2 kHz/cm², approximately equal to the associated CSC stations they complement. The ME0 station, instead, is expected to operate in a much harsher radiation environment. Tab. 4.1 shows the expected or measured background particle fluxes in different detector subsystems instrumented by MPGDs at the four major LHC experiments, together with the active area of each detector module. Among the large-area gaseous detectors (with a surface higher than 1000 cm²), ME0 is the station with the highest expected background particle flux, making it a frontier case in which MPGDs have not yet been operated.

The background radiation in ME0 is expected to be made mostly of electrons and charged hadrons; in Fig. 4.1, a simulation of the CMS detector based on Geant4 [62] shows the time distribution of the ME0 background relative to a beam collision, with most of the background particles originating within 100 ns from the primary interaction (prompt component) and a delayed component – originating from the detector materials undergoing neutron capture –

	LHCb [61]	ATLAS [29]	CMS [49]	CMS [45]	CMS
Station	M1	NSW	GE1/1	GE2/1	ME0
Technology	3-GEM	MicroMegas	3-GEM	3-GEM	3-GEM
Module area (cm²)	480	20000	4000	4000	3000
Max. rate (kHz/cm²)	600	15	5	1.5	200

Table 4.1: Comparison of the expected or measured rates in detectors instrumented by different MPGD technologies at LHC experiments, together with the surface of a single detector module.

made mostly of electrons extending up to 10 s.

A simulation of the profile of the background particle flux in the ME0 detector¹ is shown in Fig. 4.2: the average expected flux is between 2 and 200 kHz/cm², respectively in the lowest and highest pseudorapidity region, with an average of 22 kHz/cm². The simulated distribution of the energy deposit is shown in Fig. 4.3: the average energy deposit is 5.9 keV, corresponding to approximately 200 primary electron-ion pairs per event in Ar:CO₂ 70:30. Only 0.75% of the hits are due to highly-ionizing particles (HIPs), i.e. particles with an energy release higher than 30 keV (1000 primary electrons).

The baseline layout of the GEM foils for the ME0 detector is similar to the design of the GE1/1 and GE2/1 foils, with a segmentation along the η direction in 29 sectors to reduce the discharge energy (see Sec. 3.1.1); Fig. 4.4 shows the integrated background particle rate expected on the ME0 detector for each sector; the particle rate spans from 1 to 20 MHz between the lowest and highest- η sector.

4.2 Rate capability of triple-GEM detectors

There are two major effects in the physics of gaseous detectors known to affect their rate capability: space charge and resistive voltage drops. The first is known to affect mostly traditional gaseous detectors, such as multi-wire proportional chambers, while the resistive effects are mostly observable in resistive detectors such as RPCs.

4.2.1 Space charge

Space charge is the local distortion of the electric field in the gas due to high concentration of the slow charges contained in the avalanche, typically ions. In traditional gaseous detectors such as wire chambers, where the avalanche multiplication happens at a distance of a few μm from the anode wire, the drift time of the positive ions to the cathode is long enough to lower the amplification field appreciably by a time of the order of few μs , thus limiting the rate capability of the detector to a few kHz/mm² (Fig. 4.5), [64].

¹Performed in the High-Luminosity LHC scenario, which foresees an instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$; for the ultimate-high-luminosity scenario, corresponding to an instantaneous luminosity of $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, the rates have to be rescaled accordingly.

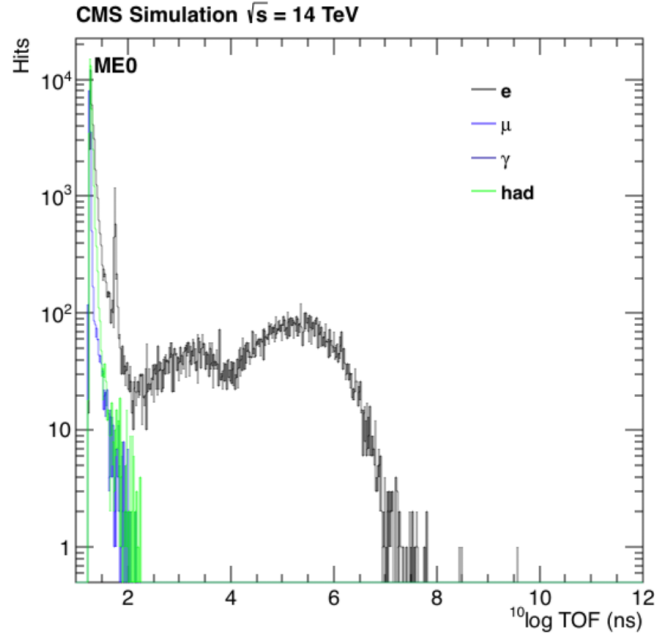


Figure 4.1: Simulated arrival time distribution of the background radiation in the ME0 detector[63].

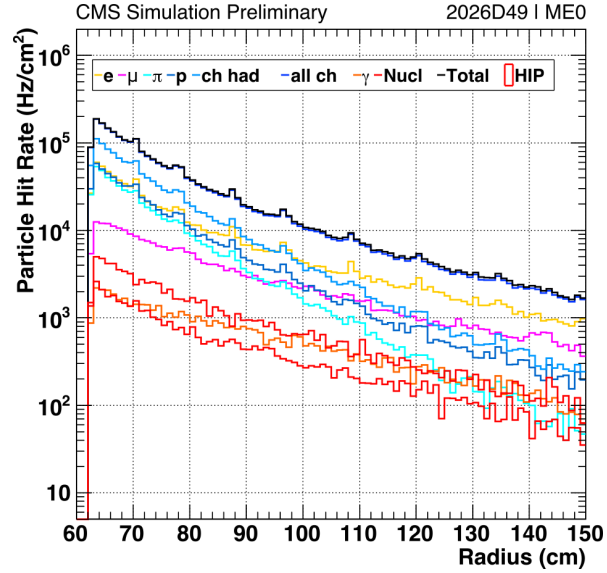


Figure 4.2: Simulated profile of the background radiation in the ME0 environment as a function of the distance from the LHC beam line. The ME0 detector will occupy the position in r between 63 and 142 cm [63].

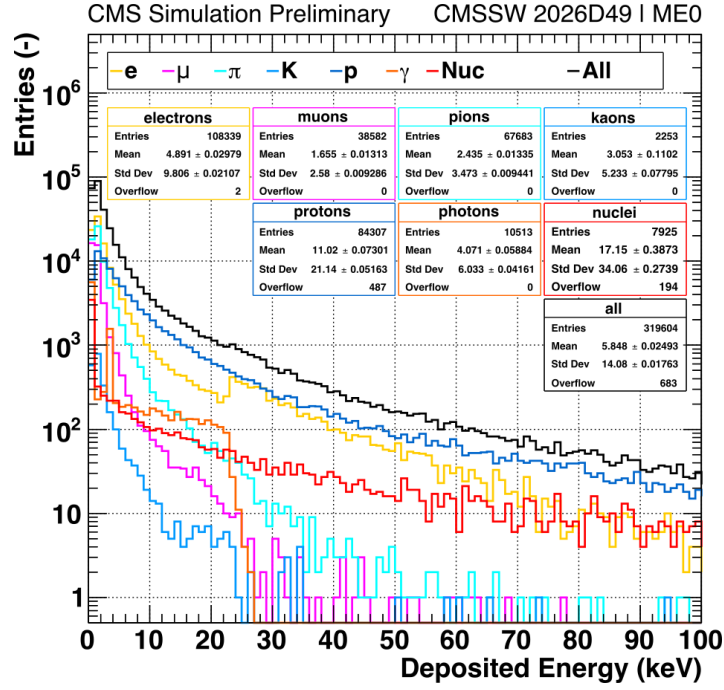


Figure 4.3: Simulated spectrum of the background energy deposit in the ME0 detector [63].

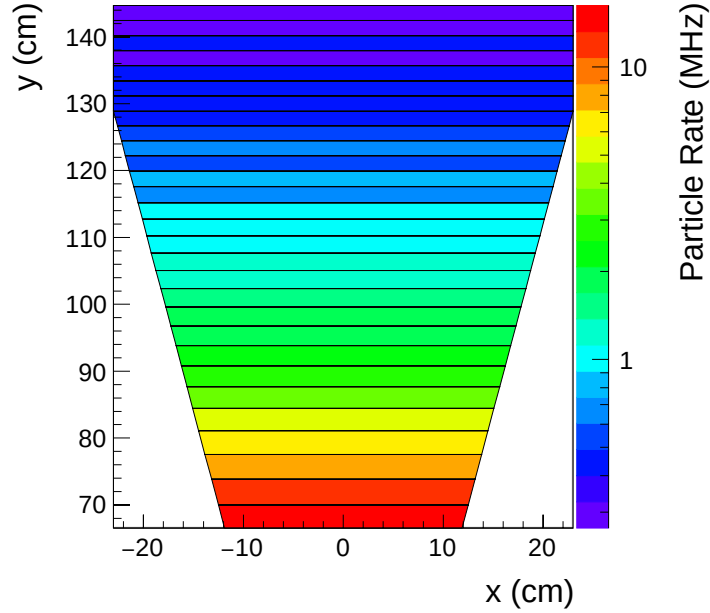


Figure 4.4: Simulated background particle rates per GEM foil sector in the baseline (horizontal) ME0 segmentation.

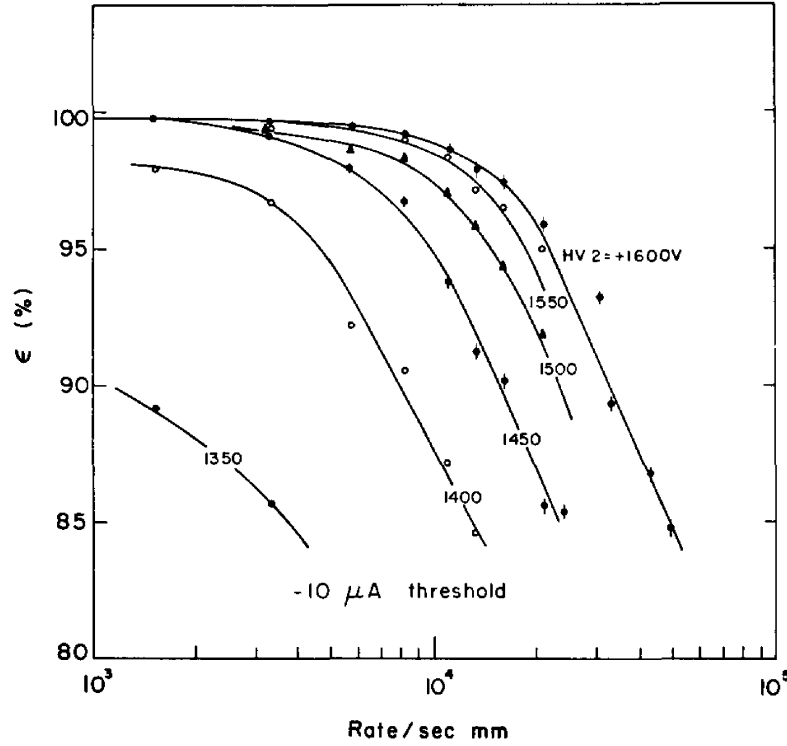


Figure 4.5: Rate capability of a drift chamber for different bias points [64].

One of the distinguishing features of MPGDs among other gaseous detectors has been the reduced distance between cathode and anode to decrease the collection times of the ions. In a GEM foil, cathode and anode (respectively, the top and bottom electrode) are separated by a distance of $50 \mu\text{m}$; at amplification fields of approximately 80 kV/cm , the ion drift velocity in argon-based mixtures is linear with the electric field and of the order of a hundreds of $\mu\text{m}/\mu\text{s}$, thus ensuring a recovery of the electric field in a few hundreds of ns. Furthermore, the electric field in a single GEM hole is decoupled from the neighbouring ones, so a large ion concentration in a single hole does not influence the charge amplification in the rest of the foil.

Being a local effect, ion space charge can be investigated in a GEM detector by irradiating a small region (of a few mm^2) with high fluxes. Measurements performed on triple-GEM detectors with 8 keV x-rays both on small prototypes and on CMS large-area detectors (Fig. 4.6 from [65]) have shown a good charge linearity up to tens of kHz/mm^2 , while at higher fluxes the effective gain increases up to 10% more than the nominal one. No gain drops have been observed up to fluxes of 2 MHz/mm^2 .

The gain dependency on the particle flux, showing an increase at high rates, has been confirmed by solving numerically the diffusion equation in gases with finite-element methods ([66, 67]). Simulations of the avalanche formation in a single GEM hole ([68]) have shown that at high fluxes the space charge effect from the backflow ions increases the extraction and

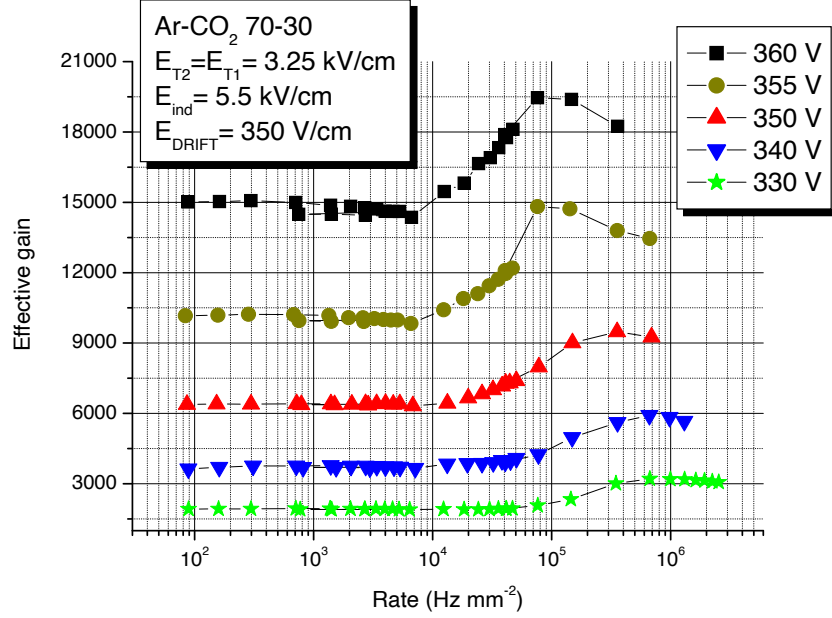


Figure 4.6: Effective gain of a triple-GEM detector irradiated by x-rays as a function of the particle flux, from [65]. Each curve is obtained for a fixed value of the voltage difference on the three GEM foils.

collection efficiencies of the electrons (Fig. 4.7).

4.2.2 Voltage drop on protection resistors

Traditionally, GEM detectors are operated with quenching resistors (see Sec. 3.1.1) for discharge protection and, in segmented GEM foil, for decoupling the sector voltages. When a detector is irradiated continuously, the drift of charges in the gas towards the electrodes induces a current flowing between the electrodes and the voltage supply (Fig. 4.8); flowing through the resistors, the current in turn induces a voltage drop that lowers the effective voltage of the GEM electrodes with respect to the supplied one. The electric field in the gas is altered and the effective gain is generally diminished, due to the lower charge amplification in the holes and transfer efficiency in the gaps.

The effect is in principle similar to the main phenomenon limiting the rate capability of RPCs [69] and resistive MPGDs such as the μ -RWELL (Fig. 4.9, from [42]). The main differences between the case of GEMs and resistive detectors are two:

- resistive detectors embed the resistive elements in their electrodes, so the voltage drop under irradiation is localized to the irradiated area; in GEM detectors, instead, the irradiation of a portion of the GEM foil sector causes a voltage drop equal to $I_{\text{electrode}} \times R_{\text{electrode}}$ on each electrode that affects the entire sector;
- in triple-GEM detectors the direction of the current flow per each electrode depends on the operating point of the other GEM foils, which have to be taken into account to

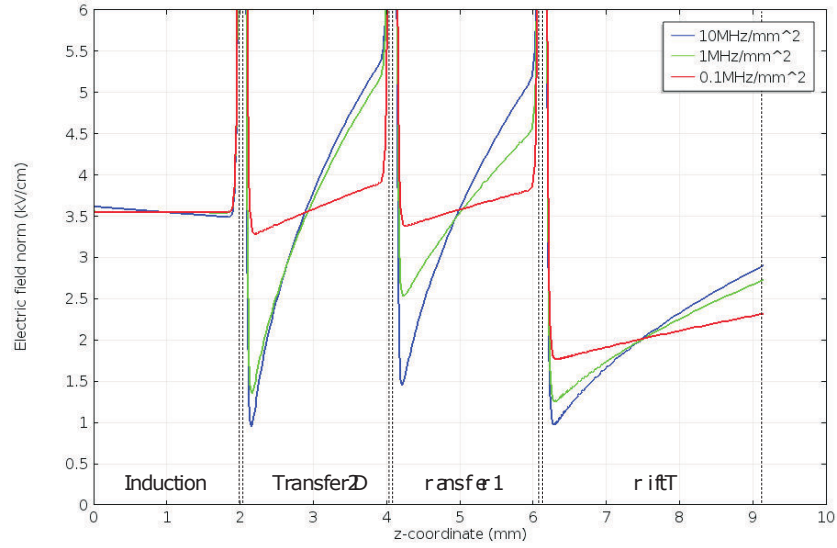


Figure 4.7: Simulated electric field in a GEM hole under irradiation by 8 keV x-rays, from [67], showing the distortion in the transfer gap electric field due to the ion space charge.

determine whether a gap or foil will show an increase or decrease of the electric field under irradiation.

With the typical protection resistors values (of the order of $1\text{ M}\Omega$) used on GEM foils, currents of tens of μA flowing on a single sector can cause voltage drops of tens of volts per foil, with an observable loss of gain and efficiency. Such currents per electrode are typically not reached in a detector irradiated with high particle fluxes (hundreds of kHz/cm^2) in small areas either in laboratory measurements or in a real-condition experiment; this is the reason why, despite being a well-known effect, the resistive gain drop has not been quantified precisely in the first applications of GEM detectors.

The precise quantification of the expected gain drop is essential instead in the case of the

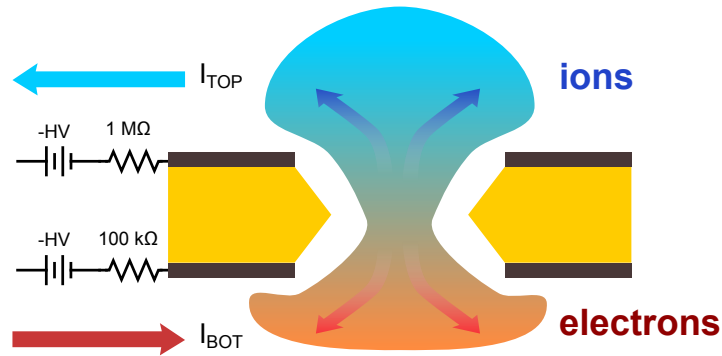


Figure 4.8: Scheme of the avalanche-induced currents flowing through the protection resistors of a single GEM foil.

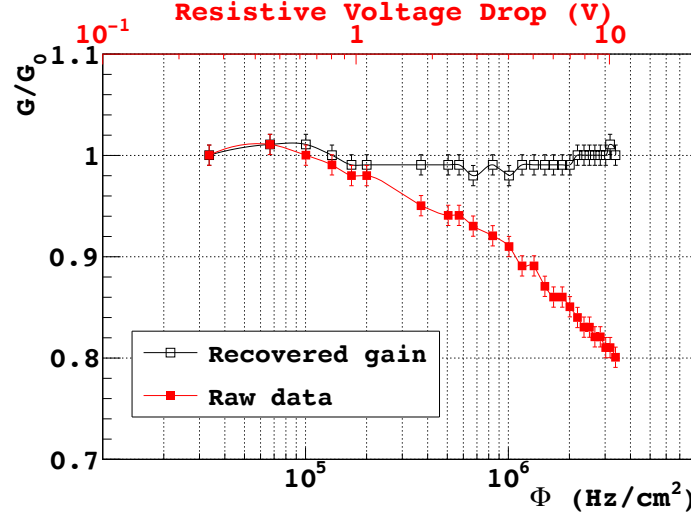


Figure 4.9: Effective gain of a μ -RWELL as a function of the background particle flux, from [42]. The black points show the effective gain after the voltage recovery obtained by applying an overvoltage to the amplification foil equal to the voltage drop under irradiation.

ME0 station, which is a large-area detector (0.3 m^2 per module) irradiated with moderate-to-high particle fluxes (up to 200 kHz/cm^2). A rough guess of the expected current flowing on the third GEM foil is

$$I = g_{\text{eff}} \times n_{\text{primaries}} \times q_e \times \phi \times A, \quad (4.1)$$

where g_{eff} is the detector effective gain, $n_{\text{primaries}}$ is the number of primary electrons per background hit, q_e is the electron charge, ϕ is the interacting background particle flux and A is the area of a single GEM sector. In the GEM foil sector in the highest-pseudorapidity region of ME0 (of surface 100 cm^2 in the baseline segmentation), the current calculated by using this formula would be of $9.6\text{ }\mu\text{A}$.

4.3 Rate capability measurement on $10 \times 10\text{ cm}^2$ detector

A direct measurement of the rate capability of a triple-GEM prototype has been performed to confirm the gain drop expected from the approximate calculation. The gain drop is expected to depend exponentially on the current flowing on each electrode ($\delta g_{\text{eff}} = e^{-\delta V} = e^{-IR}$), but an easy calculation of the effect of each GEM foil on the gain drop is not possible for the following reasons:

- the sign of the current depends of the ratio between the numbers of electrons and ions collected by the electrode; therefore, one does not know which electrodes are subjected to drops or increases in voltage;
- the current flowing on each electrode does not depend on the effective gain of the entire detector, but on the partial amplification up to each foil in the stack;

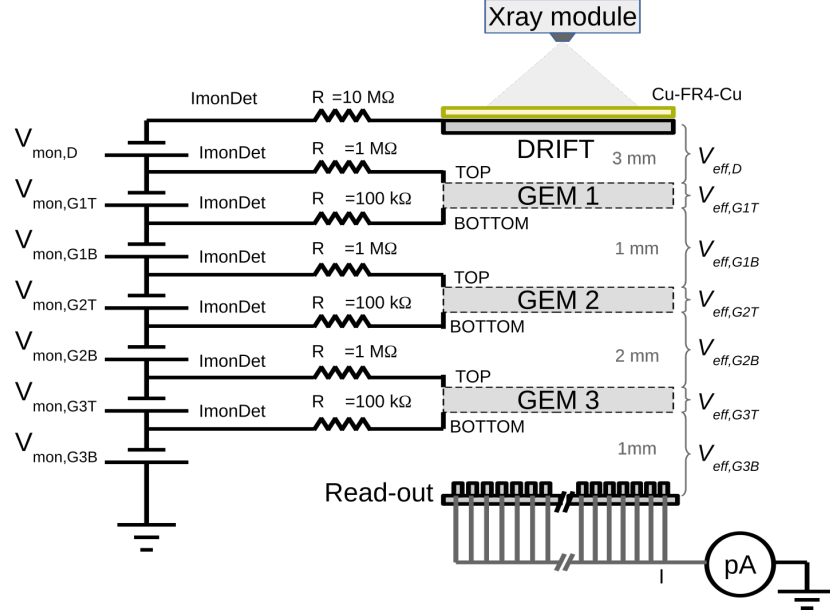


Figure 4.10: Setup for the rate capability measurement on the $10 \times 10 \text{ cm}^2$ prototype.

Foil	Resistor top	Resistor bottom
Drift	10 M Ω	
GEM 1	1 M Ω	100 k Ω
GEM 2	1 M Ω	100 k Ω
GEM 3	1 M Ω	100 k Ω

Table 4.2: Protection resistors in the $10 \times 10 \text{ cm}^2$ prototype used for the rate capability measurement.

- the linear dependency of the current on the effective gain (Eq. 4.1) is true only at first order, since the gain itself depends on the flux.

4.3.1 Detector and setup

The measurement has been performed on a $10 \times 10 \text{ cm}^2$ triple-GEM prototype, to avoid at first the complication of an ME0 detector – since under non-uniform irradiation the different GEM foil sectors would receive different particle rates and undergo different gain drops. The protection resistors of each GEM foil were the same as for the GE1/1 and GE2/1 design and the baseline ME0 design, as shown in Tab. 4.2; In order to limit the possible rate capability effects to the protection resistors alone, no high-voltage filter was used. The detector was irradiated simultaneously by two silver-target x-ray generators [70] at increasing fluxes (Fig. 4.10); within a single measurement, the distance of the source from the detector was gradually decreased to span a wider range of particle rates from 200 kHz to 20 MHz over the entire detector surface.

The detector under study was powered to a nominal gas gain of 2×10^4 through a CAEN A1515 power supply, that allows monitoring of the currents on the cathode and GEM electrodes with an accuracy of 100 pA. The anode current was measured by an ammeter of resolution 1 pA.

First observation on the currents under irradiation. Fig. 4.11 shows the trend of the current on each electrode as a function of the power of the x-ray gun with low-rate irradiation. The currents flowing on the top GEM foil electrodes and in the drift are positive (mostly ions are being collected), while on the bottom GEM electrodes and the anode the induced current is negative. Fig. 4.12 shows the voltage difference in each gap and each foil obtained by calculating the overvoltage or voltage drop under irradiation of each electrode from Ohm's law; under irradiation, all the foils sustain an undervoltage, which means the amplification is always lowered, while the electric fields in the gaps between foils increase, thus increasing the collection efficiency. The third GEM foil has the highest drop in voltage; the induction field (keeping into account that the induction gap thickness is 1 mm, twice lower than the second transfer gap) has the largest increase.

4.3.2 Rate measurement

The typical rate of traditional laboratory counting electronics is limited by pile-up to about 1 MHz, lower than the maximum particle rate achievable in the setup. Therefore, the hit rate was extrapolated from the anode current (measurable with good linearity up to 20 mA) with a procedure outlined below.

4.3.2.1 Measurement of the number of primary electrons

An essential parameter in the quantification of both interacting rate and gain drop is the average number of primary electron-ion pairs per event in the drift gap; the number of primaries depends ultimately on three factors:

- the energy spectrum of the source;
- the layers between the source and the drift gap (for example the cathode or the drift PBC);
- the energy spectrum of primary ionization from the source in the gas mixture.

To determine the average number of primaries from the x-ray, the detector anode strips are read out in OR by a charge sensitive preamplifier (Ortec 142PC) followed by a multi-channel analyzer (MCA) to measure its charge spectrum. The calibration of the MCA ADC to primary electrons is done using two sources of sharp energy spectrum, ^{55}Fe and ^{109}Cd . The former has a spectrum in argon with a peak at 5.9 keV and an escape peak at 2.7 keV, equal to the difference between the main peak energy and the argon escape peak energy (3.2 keV). The second source, instead, emits x-ray photons peaked at 22 and 22.5 keV, which have a low ionization cross section in the Ar:CO₂ mixture and is weakly resolved; the signal spectrum peaks at 8 keV, the energy of fluorescence of the copper in the cathode.

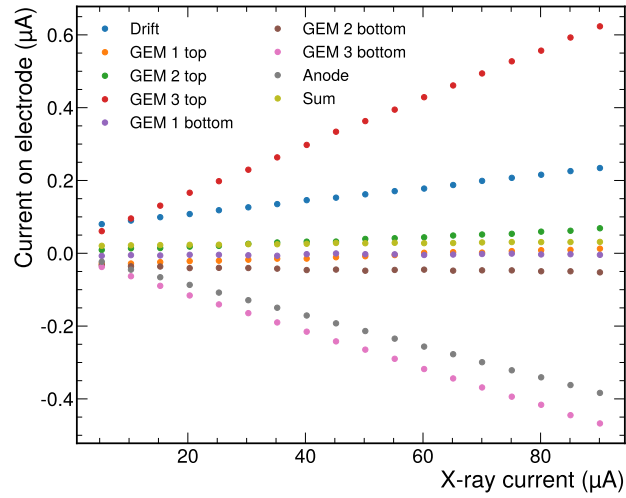


Figure 4.11: Current flowing on each GEM electrode under irradiation as a function of the x-ray gun current. The sum of all the currents is zero, as expected by conservation of charge.

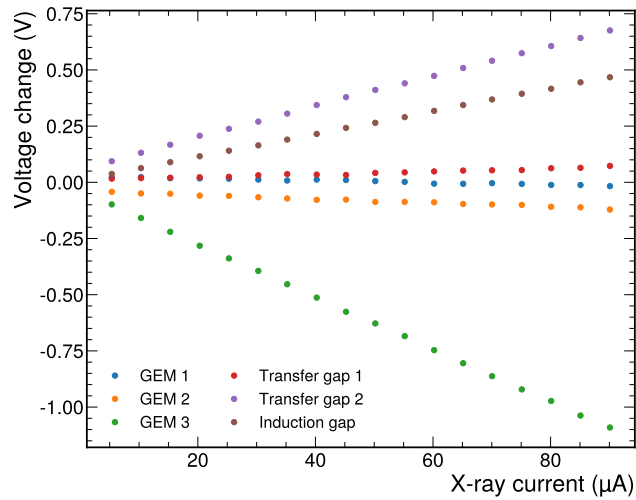


Figure 4.12: Voltage difference on each GEM foil and gap under irradiation as a function of the x-ray gun current.

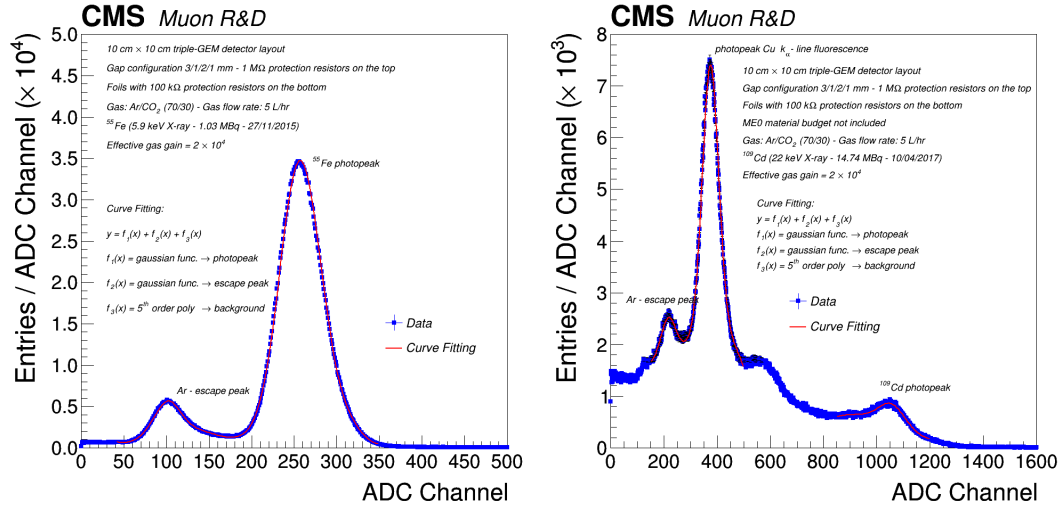


Figure 4.13: Spectra of a ⁵⁵Fe (top) and ¹⁰⁹Cd sources irradiating the 10×10 cm² detector.

The Fe and Cd energy spectra (Fig. 4.13) are measured and the position of each known energy peak is fitted with a gaussian function; the MCA calibration curve is obtained from a plot of the peak position fitted with a linear function, as shown in Fig. 4.14. Finally, the ADC spectrum of the x-ray gun is converted to an energy spectrum using the calibration curve just obtained. The conversion factor between the energy spectrum and the number of primary electrons is the average ionization energy of Ar:CO₂ 70:30, i.e. 28.3 eV.

As a final step, between the source and the 10×10 cm² prototype a 3 mm thick layer of FR4 is placed to emulate more closely the material budget of the ME0 detector. Differently from the 10×10 cm² prototype, indeed, the drift electrode in an ME0 detector is enclosed in a 3.2 mm-thick PCB (in turn wrapped in two 35-μm thick copper layers, which have a negligible impact on the spectrum) instead of a kapton foil. A Monte Carlo simulation using Geant4 has been developed to estimate the effect of each layer in the detector between the source and the gas on the x-ray spectrum (Fig. 4.15). The FR4 layer is shown to have a strong effect in the absorption of low-energy x-rays, thus increasing the number of primaries.

Fig. 4.16 shows the energy spectrum measured with the detector with the additional material layers; the average number of primary electrons is 348.

4.3.2.2 Rate measurement from current extrapolation

The anode current was measured with increasing flux of the x-ray sources (Fig. 4.17a). The saturating trend is due to the gain drop of the detector. The current curve was fitted with the parametric function

$$i_{\text{anode}} = \frac{AI_{\text{xray}} + B}{1 + k(AI_{\text{xray}} + B)}, \quad (4.2)$$

(where I_{xray} is the current powering the x-ray source and k is a parameter quantifying the bending of the curve) and then linearized to obtain the anode current that would be measured

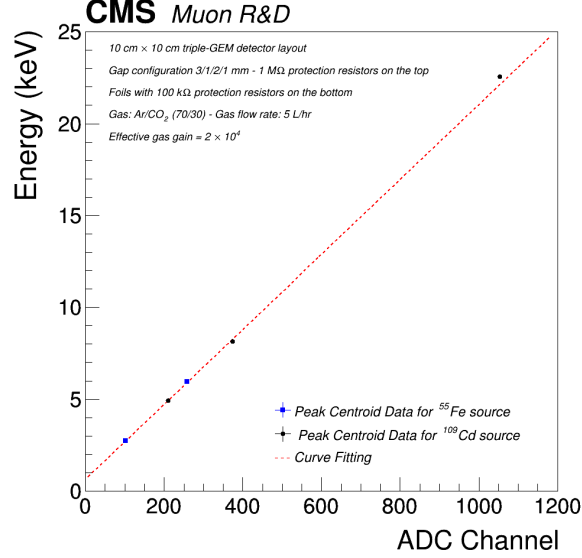


Figure 4.14: Calibration curve of the MCA in energy obtained from the ^{55}Fe and ^{109}Cd sources.

on the detector in absence of gain drop.

The rate on the chamber (Fig. 4.17b) was finally calculated from the linearized current by inversion of the effective gain equation:

$$R_{\text{extrap}} = \frac{i_{\text{linearized}}}{qe n_{\text{primaries}} g_{\text{nominal}}}, \quad (4.3)$$

where g_{nominal} is the detector effective gain in absence of background flux.

4.3.3 Gain drop measurement

The effective gain of the detector under irradiation was determined separately – for each rate point – by two independent methods.

The first gain estimation (“direct” method) is obtained by the effective gain equation:

$$g_{\text{eff}} = \frac{i_{\text{anode}}}{qe n_{\text{primaries}} R_{\text{extrap}}}, \quad (4.4)$$

where R_{extrap} is the particle rate as determined with the procedure described above. The main source of uncertainty in this measurement is the rate extrapolation error.

In the second gain measurement, each electrode is powered at an “effective” voltage obtained from the nominal voltage supplied by the power module by subtracting the voltage drop on the corresponding protection resistor:

$$V_{\text{eff}}^i = V_{\text{set}}^i - I_{\text{mon}}^i R_{\text{protection}}^i, \text{ with } i = \text{drift, GEM 1 top, GEM 1 bottom etc.} \quad (4.5)$$

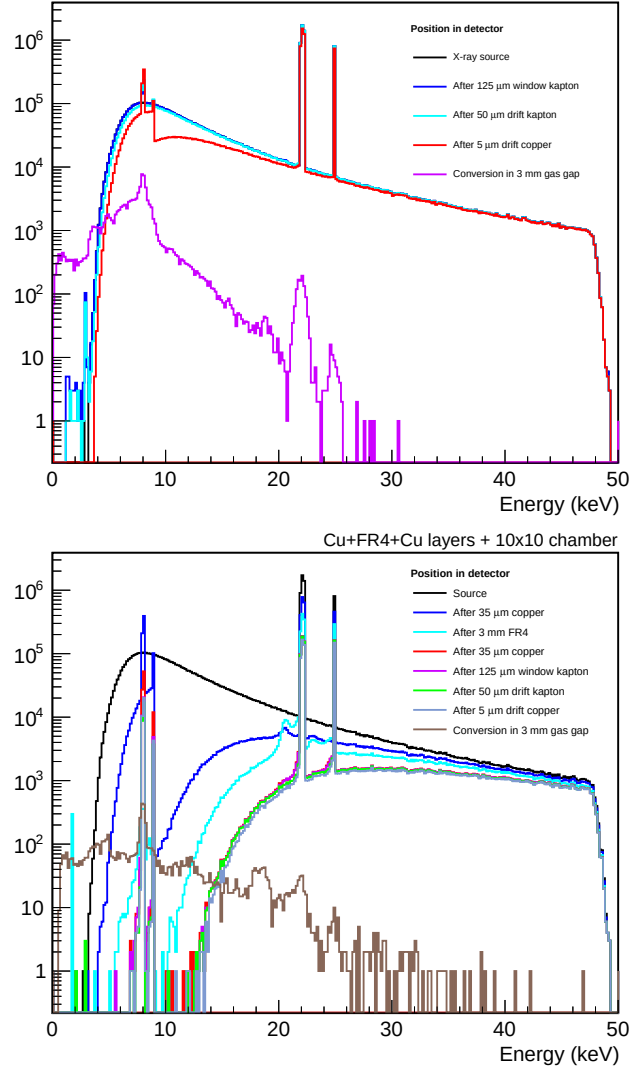


Figure 4.15: On top, spectrum of the x-ray gun photons after interaction with the all the layers on the drift side of the $10\times 10\text{ cm}^2$, including the gas in the drift gap, simulated with Geant4. On the bottom, spectrum obtained adding two 35- μm layers of copper and a 3-mm layer of FR4 in front of the $10\times 10\text{ cm}^2$ to reproduce the material budget of an ME0 detector. The spectrum of the gun is reproduced as bichromatic and made of two peaks at 22.5 and 25 keV.

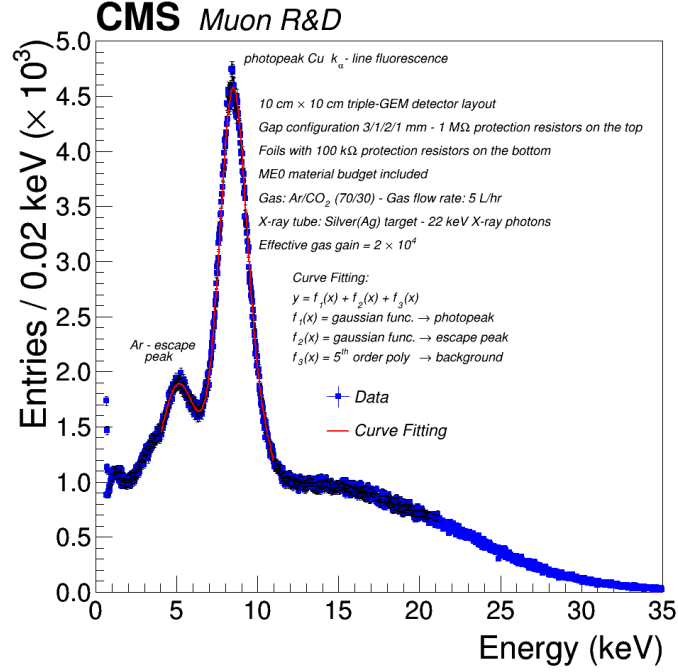


Figure 4.16: Spectrum of the x-ray gun irradiating the $10 \times 10 \text{ cm}^2$ detector with the addition of the FR4 layer after the energy calibration is applied.

A gain measurement is performed at such “effective” bias point at low irradiation by an x-ray source, measuring the particle rate with a preamplifier and a scaler. The gain estimated with this procedure is more accurate than the former because it is a direct measurement, but it is only sensitive to gain variations traceable to the “ohmic” effect, i.e. the voltage drop on the protection resistors.

4.3.4 Results from the rate capability measurement

The rate capability curves (Fig. 4.18) obtained with the “direct” and “ohmic” experimental methods are in agreement within the measurement statistical uncertainty, proving that the only perceptible gain drop in the explored rate interval is due to the already discussed “resistive” effect.

The highest gain drop observed in the laboratory measurements is 40% of the expected gas gain, observed at an irradiation of 100 kHz/cm^2 . However, such value depends on the irradiated detector surface and the values of the protection resistors on each electrode.

To relate the measurements performed in the laboratory to the ME0 environment, one has to consider the different detector geometry of an ME0 module with respect to a $10 \times 10 \text{ cm}^2$ prototype and the different energy spectrum of the ME0 background with respect to the x-ray source. The following sections show the assumptions to rescale the rate capability results to the ME0 case, discuss the implications on the ME0 performance and the adopted mitigation strategies.

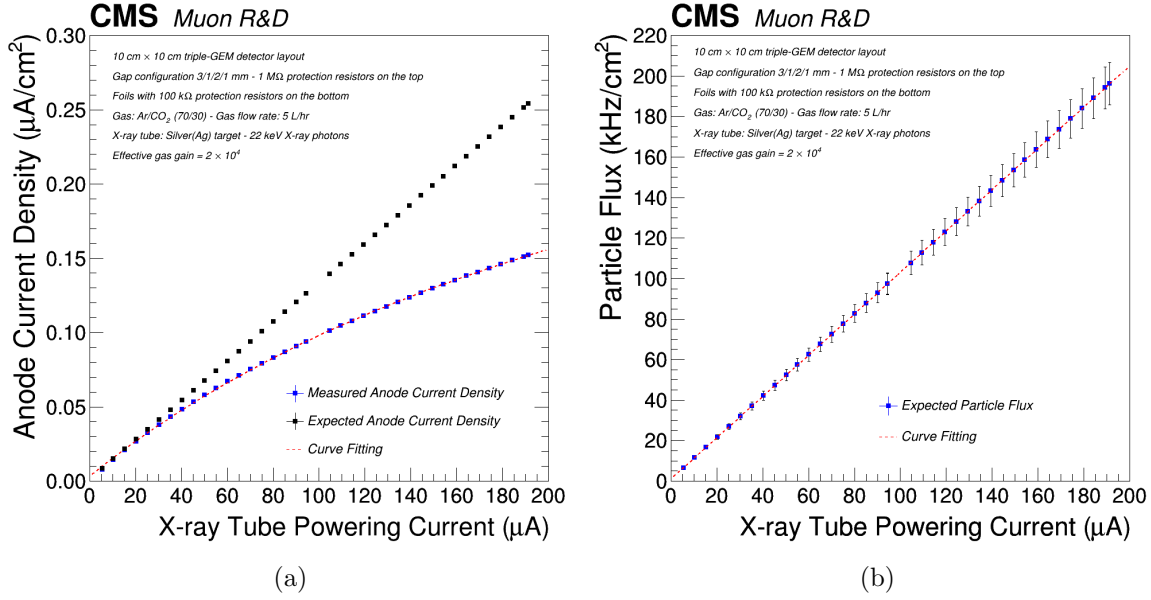


Figure 4.17: (a) Anode current of the detector as a function of the x-ray tube powering current (blue) and linearized anode current (black). (b) Hit rate on the detector as a function of the x-ray current obtained by inversion of the effective gain equation.

4.3.5 Estimated ME0 rate capability

The first conclusion from the laboratory measurements is that the only observable effect on the rate capability at rates up to $200 \text{ kHz}/\text{cm}^2$ is the resistive voltage drop. As discussed earlier, such gain drop affects the whole foil and at fixed integrated particle rate is independent of the area of the irradiated surface. For a detector with segmented foils, the gain drop on each sector depends only on the background rate on the sector itself. Therefore, the rate capability curve can be expressed as a function of the total particle rate by rescaling the axis by the active area of the $10 \times 10 \text{ cm}^2$ prototype to obtain a result that is independent of the sector surface. Secondly, the rate axis can be rescaled to keep into account the different number of primary electrons between the ME0 background and the x-ray source (348 in the laboratory measurement against 200 in the ME0 background simulations). The resulting curve (Fig. 4.19) shows an approximate guess of the expected gain drop in the ME0 background environment, with a gain loss of 40% at a particle rate of 20 MHz per foil sector. This is a realistic value for the gain drop – in absence of high voltage filter and with only $1 \text{ M}\Omega$ protection resistors – in the highest- η region of an ME0 detector (see Fig. 4.4).

4.4 Gain recovery by voltage drop compensation

A possible method to recover the nominal gain of the detector under irradiation consists of applying an overvoltage to each electrode to compensate for the irradiation-induced voltage drops, as inspired by the efficiency recovery techniques already tested with RPCs and resis-

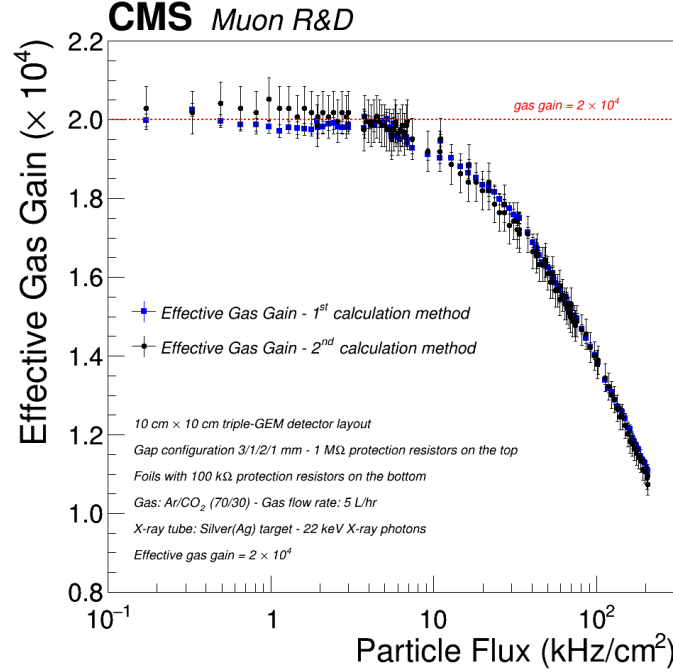


Figure 4.18: Gain drop of the irradiated prototype comparing the “direct” gain measurement (in black) and the “ohmic” gain measurement (in blue).

tive MPGDs [42]. In resistive gaseous detectors, the compensation is simply performed by increasing the bias point of the detector by a voltage equal to the drop; in the case of GEMs, however, because the bias point of the detector is not defined by a unique number².

For this reason, the gain recovery is carried iteratively. The steps for the compensation of the voltage drop at a fixed background rate are the following:

- at step 0, the voltage applied to each electrode is set to $V_{\text{set}}^{(0)} = V_{\text{nominal}} + I_{\text{mon}}^{(0)} R_{\text{prot}}$;
- at each subsequent i -th step, the voltage applied to each electrode is set to $V_{\text{set}}^{(i)} = V_{\text{set}}^{(i-1)} + I_{\text{mon}}^{(i)} R_{\text{prot}}$;
- the compensation is completed when $|V_{\text{eff}}^{(i)} - V_{\text{nominal}}| < 1V$, i.e. the effective voltage on each electrode $V_{\text{set}}^{(i)} - I_{\text{set}}^{(i)} R_{\text{prot}}$ is compatible with the nominal one within a small tolerance.

Fig. 4.20 shows the iterative trend of the voltage corrections on each electrode; the compensation converges almost immediately for all electrodes except for the bottom of the third foil, the one sustaining the largest amount of current, which takes 5 to 6 iterations to converge at the largest fluxes tested.

²An equivalent divider current is defined only if the ratios between the electric fields in the holes and in the gaps are constant.

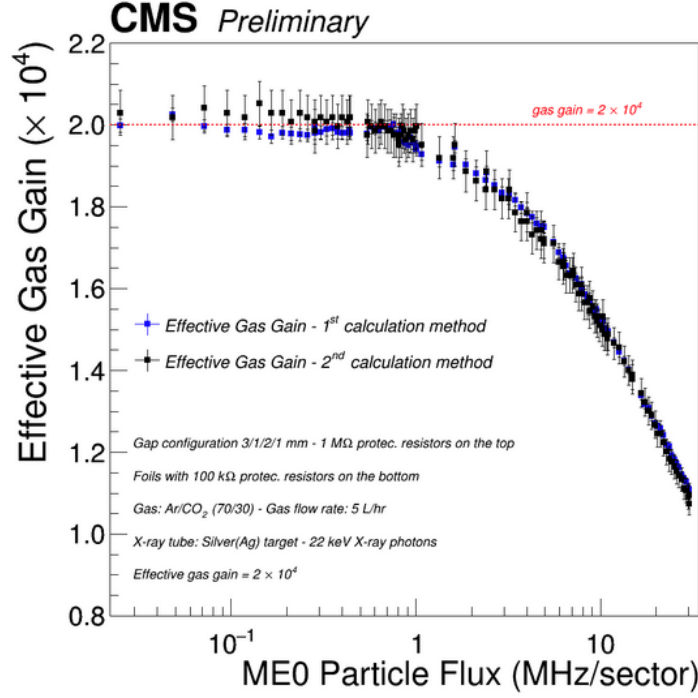


Figure 4.19: Expected gain drop in a detector irradiated in the ME0 background environment, obtained rescaling the results of the rate capability measurements on the $10 \times 10 \text{ cm}^2$ by the detector area and the expected number of primary electrons.

Fig. 4.21 shows the rate capability curve overlapping with the recovered gain curve after voltage compensation, together with the nominal gain at which the detector has to be powered to operate it at an effective gain of 2×10^4 for each value of the background rate.

The result defines a successful procedure of gain compensation by overvoltage; however, it also shows that an effective operation of the ME0 detector in the highest- η region would require a nominal gain of approximately 6×10^4 , with an increased damage risk in case of sudden beam loss during the LHC operation. Moreover, each GEM foil sector would have to be powered at a different voltage point to account for the highly uneven background rate at increasing pseudorapidity (see Fig. 4.4). The proposed solution for the two issues raised above is discussed in the next section.

4.4.1 Redesign of the GEM foil sectorization

A possible design choice for equalizing the gain drop across different GEM foil sectors and minimizing the average gain drop consists of abandoning the longitudinal foil segmentation in favor of an azimuthal sectorization with respect to the beam axis (Fig. 4.22). Since the background profile in the ME0 detector is expected to be symmetrical along the ϕ direction, the expected background rate per sector is almost identical with small variations³ and the

³The rate is not identical for all sectors because the detector shape is not perfectly axially symmetrical.

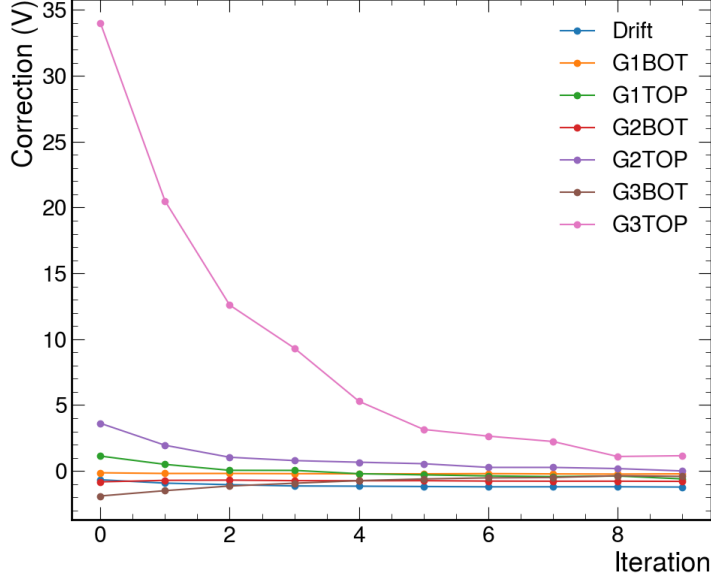


Figure 4.20: Iterative corrections applied in each electrode during the voltage compensation procedure.

average background rate per sector is inversely proportional to the number of sectors.

By combining the background flux simulations and the gain drop measured in the rate capability studies it is possible to determine an expected dependency of the gain drop of the ME0 detector with azimuthal segmentation as a function of the number of sectors (Fig. 4.23). The number of sectors has to be chosen by design to minimize the gain drop while keeping the area of each sector small enough (100 cm^2 is a rule of thumb) to still be effective to minimize the discharge energy. In a segmentation with 40 sectors the average rate per HV sector in the CMS background (Fig. 4.22) can be contained to 1.5 MHz, while the effective gain drop (Fig. 4.24) can be minimized to about 10% of the expected value of 2×10^4 .

An essential aspect to be considered in the comparison between the longitudinal and the azimuthal segmentation for future studies involves the different dead area introduced by the polyimide separation lines between two adjacent foil sectors. Considering that each separation line has a thickness of $200 \mu\text{m}$, the total dead area of a ME0 module with 40-sector azimuthal segmentation is approximately 1.75% of the detector surface, compared with about 0.1% for a 29-sector longitudinally segmented detector. The random-hole segmentation for GEM foils, already introduced in the discussion of the GEM test beam (see appendix A), can minimize the dead area induced by the sectorization; an R&D is ongoing on the production of ME0 detectors with random hole segmentation.

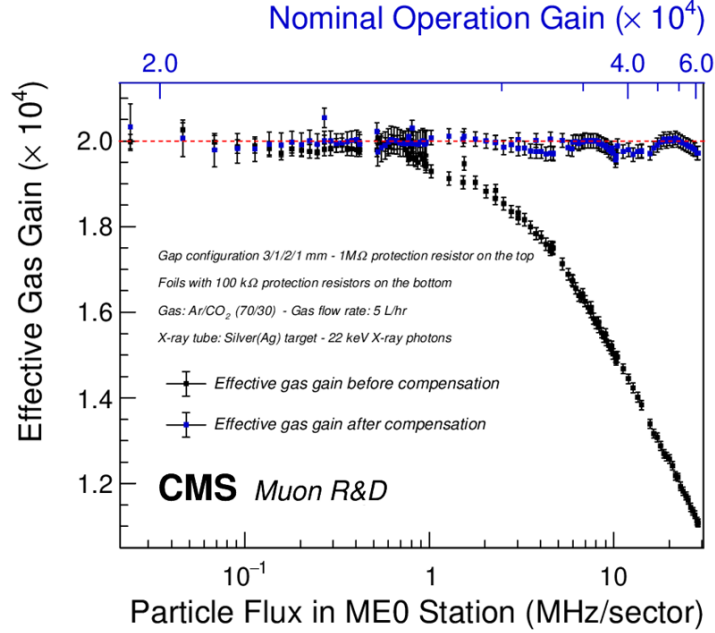


Figure 4.21: Recovered gain of the GEM detector over the tested rate region. The top axis shows the nominal gain (as per gain calibration curve) at which the detector has to be powered to operate it at an effective gain of 2×10^4 under irradiation.

4.4.2 Production and test of the second-generation ME0 triple-GEM prototypes

The first prototypes of ME0 second-generation detectors – i.e. instrumented with azimuthally-segmented GEM foils – have been designed and produced in July 2021. Fig. 4.25a shows the picture of a GEM foil with azimuthal segmentation.

The prototypes have undergone the standard QA/QC tests for the assurance of their performance compliance with the CMS requirements. Fig. 4.25b shows the result of the gain calibration curve on a prototype, with no observable difference from a traditional CMS detector. Conclusive proof of the performance stability of the second-generation design has come from the 2022 test beam discussed in the previous chapter.

4.4.3 Discussion on the effect of the high voltage filter

The rate capability measurements described in the previous sections have been performed without readout electronics, and consequently without high voltage filter used to decouple the power supply noise from the readout. However, the filter is expected to affect the rate capability of the detector, as it contains three resistors (chosen by 100 k Ω each in the GE1/1 and GE2/1 design); additionally, since the whole GEM foil is connected to a single HV filter, the current flowing in the filter resistors is the one induced on the entire GEM foil, with a high expected voltage drop. For the same reason, the voltage drop on the filter is independent

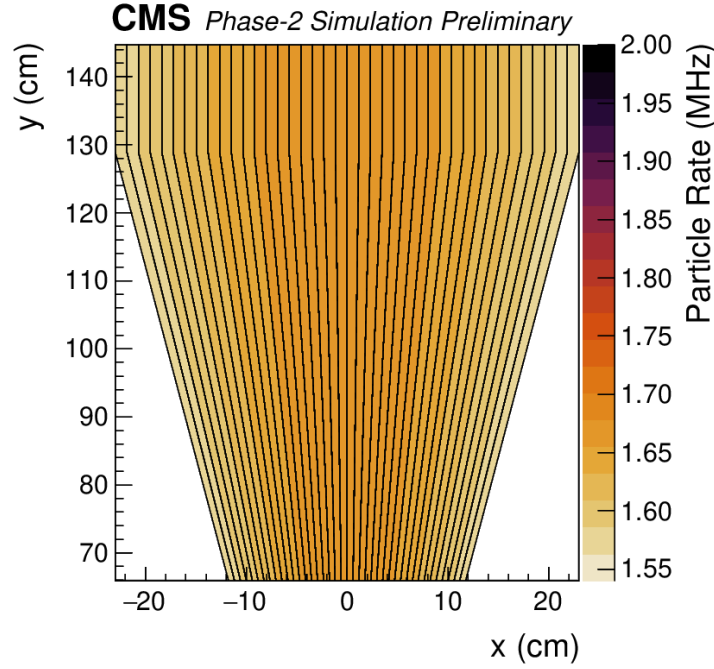


Figure 4.22: Design of the adopted azimuthal segmentation for the ME0 detectors, showing the expected background particle rate per sector in the CMS environment.

of the GEM foil segmentation.

As a consequence, a complete characterization of the impact of the HV filter on the rate capability requires a measurement under uniform irradiation on the entire detector surface, or at least in the ϕ coordinate; such test cannot be performed with a laboratory x-ray gun, which provides a non-uniform irradiation localized on a surface smaller than an ME0 detector: in this case, the gain drop is not uniform among the GEM foil sectors and the voltage compensation procedure is not well-defined. The measurement of the filter effect can be performed in a facility such as the GIF++, which can provide uniform high-rate irradiation on large areas; the second motivation for a GIF++ irradiation campaign is a rate capability measurement in test beam, as described in the next session.

4.5 Test beam in high-background environment at the GIF++

The completion of the rate capability studies would be the demonstration of the working principle of the new ME0 detector layout in background with final electronics. A suitable place for such a measurement is the Gamma Irradiation Facility [71] (GIF++) located at CERN in the North Area, on the H4 beam line. The GIF++ provides a 13 TBq ^{137}Cs radioactive source, allowing in a test beam with a tracker the measurement of MIP efficiency under uniform irradiation. A two-week test beam campaign in the GIF++ has been carried out in July 2022 with a second-generation ME0 detector and a $10 \times 10 \text{ cm}^2$ triple-GEM tracker; the following sections summarize the setup, data taking and results of the test beam with

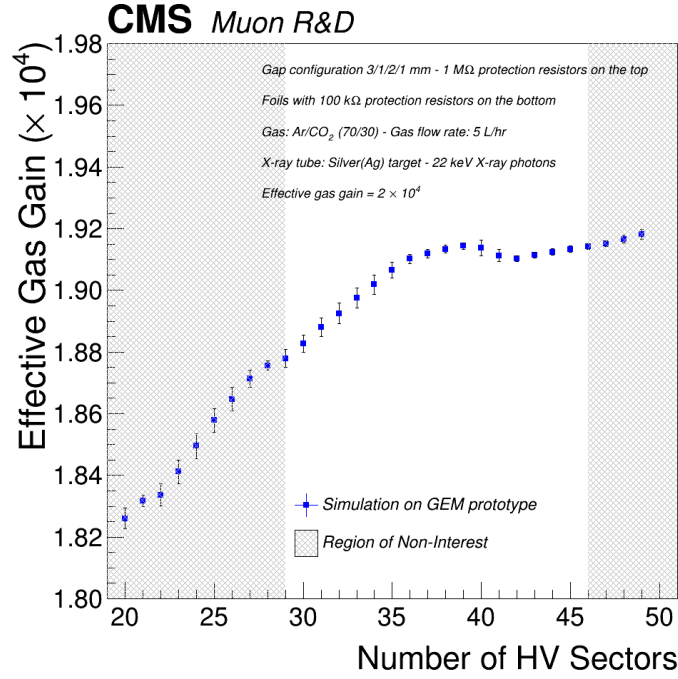


Figure 4.23: Expected average gain drop of the ME0 detectors for different number of azimuthal foil segments.

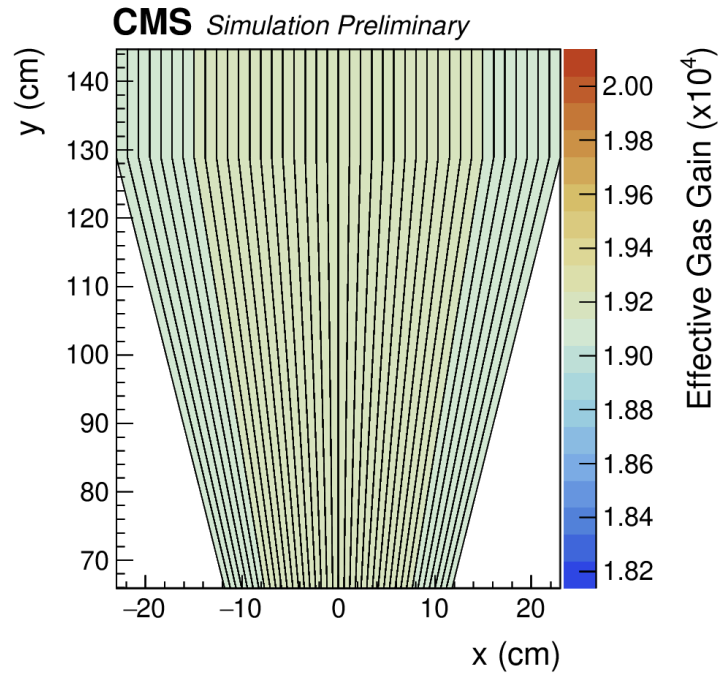


Figure 4.24: Expected gain of the ME0 detectors with azimuthal segmentation for each GEM foil sector under irradiation in the CMS environment.

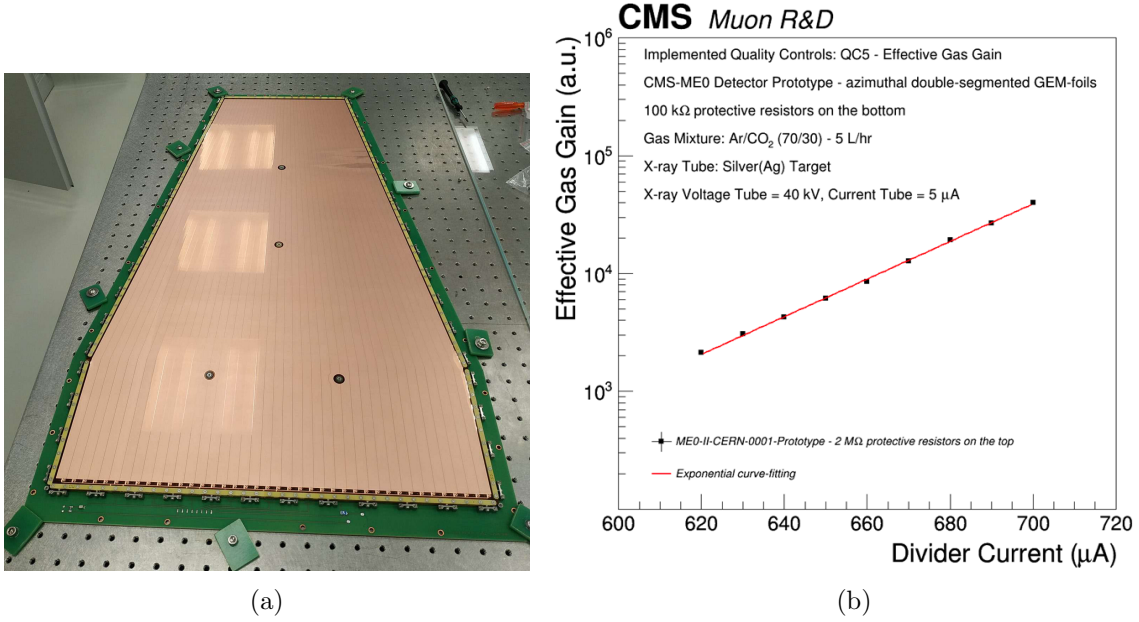


Figure 4.25: (a) Picture of an ME0 GEM foil with azimuthal segmentation. (b) Effective gain calibration curve of an ME0 second-generation detector.

comparison to the ME0 performance requirements.

4.5.1 The Gamma Irradiation Facility at CERN

The GIF++ is a facility running in the CERN North Area since 2015 [72] designed for irradiation campaigns (mostly oriented at longevity) on gaseous detectors for HL-LHC. The facility is a bunker of $12 \times 12 \text{ m}^2$ area containing a ^{137}Cs radioactive source – of activity 13.5 TBq at the time of the 2016 measurement – adjustable with two sets of intensity filters. The source emits mainly 662 keV photons and lower energy scattered photons; the latter are the ones giving the largest fraction of events in a GEM detector.

The GIF++ is placed in the downstream side of the SPS H4 line – the same line on which the Phase-2 GEM test beams have taken place –, from which it receives a muon particle beam from the production target hit by the SPS proton beam. The typical energy of the muons is of the order of 100 GeV and the beam spot in the GIF++ has a typical core of $10 \times 10 \text{ cm}^2$, surrounded by an halo extending up to 1 m^2 . The beam passes through the GIF++ bunker at a distance between 0.65 and 2.15 m from the source in the horizontal direction, as shown in the bunker plan in Fig. 4.26.

The GIF++ attenuators are a set of filters, shaped in a convex geometry to turn the spherical source flux to a planar wavefront; the background extends from the source in two cones of 37° opening in the upstream and downstream regions. For each direction, the attenuator is made of three filters (called A, B and C) each in turn divided in three layers of lead (1, 2 and 3); by combining the three filters, 27 combinations of the form (Ax, By, Cz) can be obtained, for attenuation factors ranging from 1 (lowest attenuation, highest flux) to

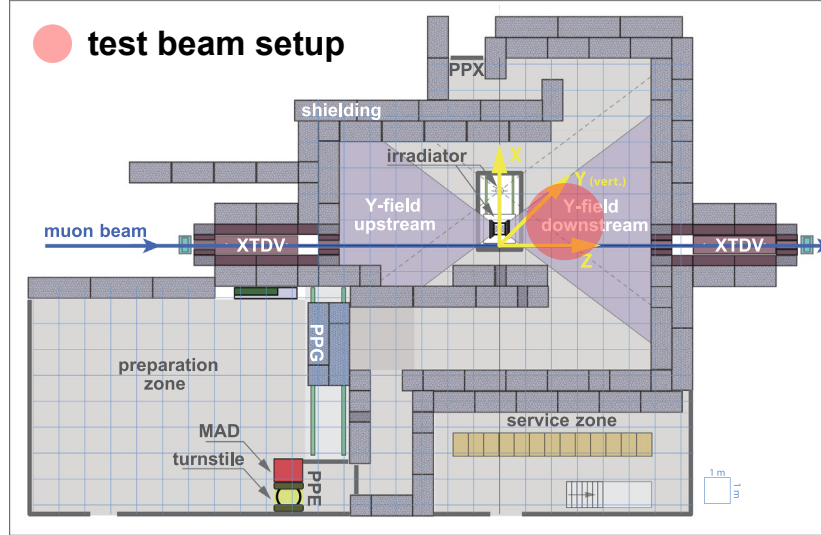


Figure 4.26: Plan of the GIF++ bunker with its system of coordinates [72].

46415 (highest attenuation, lowest flux). Each attenuation factor f_{ABS} corresponds to a total attenuator thickness x according to Lambert Beer's law: $f_{ABS} = I/I_0 = e^{-\mu x}$; the state of each attenuator can be configured from the GIF++ control room panel; Fig. 4.27 shows the design of the attenuators and the attenuation factor list.

4.5.2 Preliminary studies at the GIF++

The test beam setup has been placed in the downstream area of the GIF++, at a distance of 1.13 m from the source. The chosen position was the closest possible to the source to maximize the particle flux and the particle rate while keeping the entire detector inside the irradiation field at a distance high enough to guarantee an approximately uniform irradiation.

In preparation for the test beam, a rate capability measurement in the GIF++ field has been performed, followed by a gain compensation test. The procedure has been repeated for increasing values of the HV filter resistor from 5 up to 200 k Ω , including a measurement without HV filter. The rate capability curves for different filters, together with the compensation test result, are shown in Fig. 4.28: for an HV filter of 51 k Ω resistors, the baseline resistance chosen for ME0, the gain compensation under irradiation has been confirmed up to the highest measured rate (1.2 MHz/sector) with a nominal applied gain up to 2.6×10^4 .

4.5.3 Test beam setup

The schematic test beam setup is shown in Fig. 4.29b. The overall setup is a scaled-down version of the H4 test beams described in the previous chapter. The detector under test is an ME0 second-generation prototype (Fig. 4.29b), while the tracker is made of three $10 \times 10 \text{ cm}^2$ triple-GEM detectors; the four detectors are equally spaced at a distance of 15 cm.

Each of the four tracking detectors has two perpendicular readout planes of 400 μm strip

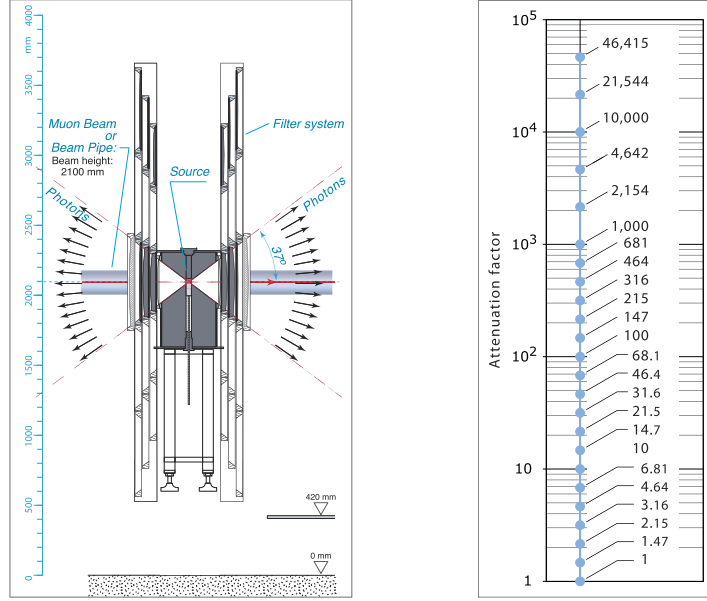


Figure 4.27: Design of the GIF++ source filters (left) and list of the attenuation factors obtainable by combining the configurations of the three attenuators (right) [72].

pitch, for an expected space resolution of $\text{pitch}/\sqrt{12} = 115.5 \mu\text{m}$. The trigger system is made of the two $30 \times 30 \text{ cm}^2$ scintillators provided by the GIF++ and two $10 \times 10 \text{ cm}^2$ scintillators placed next to the setup and aligned with the tracker; the four scintillators are read out by PMTs and the trigger signal is their coincidence.

4.5.3.1 Electronics and data acquisition

The DAQ system of the GIF++ test beam follows closely the H4 test beam architecture: the back-end FPGA is a Xilinx VU13P enclosed in a CVP-13 board, connected via PCIe to the DAQ machine; the trigger input from the photomultipliers is converted to the 1.3 V level accepted by the CVP-13 and routed to the FPGA through the SlimSAS port. The optical communication with the front-end is managed by two QSFP transceivers; a fourth transceiver hosts the connection to a network interface card for the local DAQ.

The front-end electronics of the ME0 is the pre-production electronics close to the final one. The beam irradiates only a $10 \times 10 \text{ cm}^2$ area on the wide side of the detector, that is instrumented with a wide GEB (Fig. 4.30); the narrow side is read out by a picoammeter to monitor the gain compensation and the current stability during a run under source irradiation. Nine out of the twelve read-out partitions of the wide GEB are read with VFAT3 plugin-cards, namely eta partitions from 6 to 8; eta partition 5 is not read out since it is not irradiated by the beam. In total, the beam-irradiated fraction of the ME0 is read out by two ME0 OptoHybrids, in turn connected to one QSFP in the CVP-13.

Each of the tracking detectors is read out by four VFAT3 hybrids (two for each readout plane, for a total of 256 strips per plane); the twelve VFATs of the tracker are connected

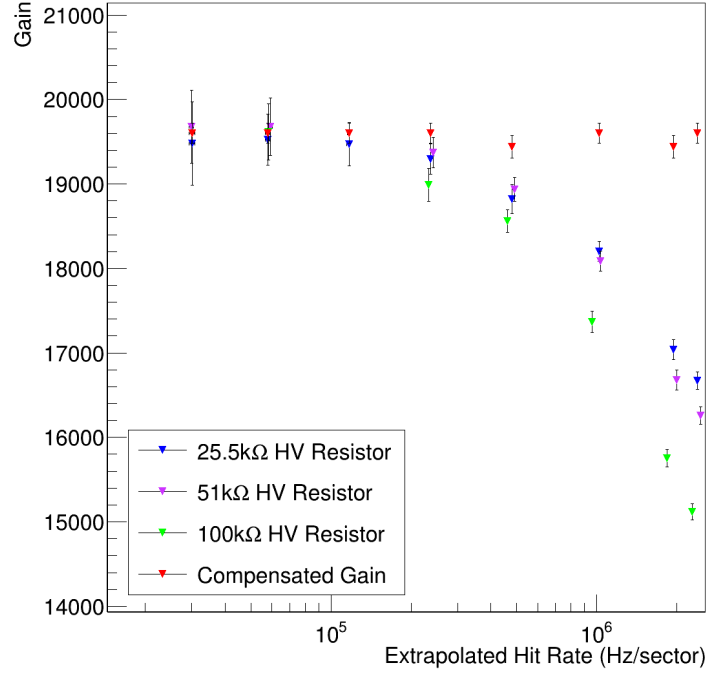


Figure 4.28: Rate capability measured at the GIF++ for different HV filter resistors and recovered gain [73].

through firefly cables to a GE2/1 GEB, in turn connected to another QSFP in the back-end board.

4.5.4 Rate measurement at the GIF++ with final electronics

A direct high-granularity measurement of the background rate at the GIF++ was needed as a benchmark for the current measurements and to ensure the uniformity of the background flux over the detector surface. The DAQ path was used to estimate the background rate with single-strip precision on all four detectors. In all rate measurements, the detectors have been powered with high-voltage compensation to ensure their maximum efficiency under irradiation.

A first benchmarking measurement was performed on the three tracking detectors at VFAT3 level (i.e. counting the OR of all strips of each VFAT) to compare the rate measured from the DAQ and the s-bit paths. In the s-bit measurement, the background rate is obtained directly from the s-bit counter implemented in the OptoHybrid; for the DAQ measurement, the rate is measured with a 50 kHz cyclic trigger obtained from the CVP-13 TTC generator, configuring the VFATs for pulse stretch zero. In the latter case, the rate is calculated from the number of events ν_i in which at least one of the channels in the i -th VFAT3 recorded a hit with the equation:

$$f_i = \frac{\nu_i}{n \cdot 25 \text{ ns}}, \quad (4.6)$$

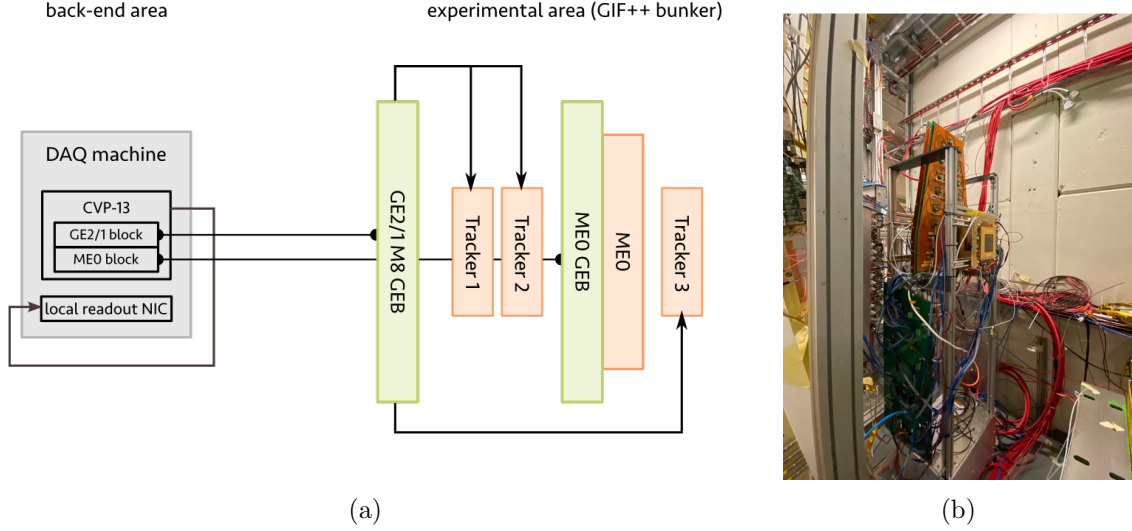


Figure 4.29: Schematic setup (a) and picture (b) of the GIF++ test beam.

where n is the total number of triggers.

Fig. 4.31 shows the resulting rate scan as a function of the GIF++ source attenuation for tracking detector 2. For all three detectors, the rate per VFAT3 measured from the s-bit counter is compatible with the rate measured from the DAQ path; this ensures the validity of the rate measurement through the DAQ path, which is a less direct technique than the s-bit counting.

In the case of the ME0 detector, the only possible rate measurement is through the DAQ path itself, since the ME0 OptoHybrid does not have an FPGA for the s-bit counting and the s-bit module is not implemented in the CVP-13 firmware⁴. Furthermore, the DAQ path gives the only available measurement of the background profile with strip-by-strip granularity.

The rate per strip is measured with the same formula as in Eq. 4.6, ν_i being the number of events in which the i -th strip has recorded a hit.

Fig. 4.32 shows the profile of the background rate on the eta partition 1 of the ME0 detectors with no source attenuators. The rate profile is flat within the entire detector surface, as expected from the GIF++ specifications: at a distance of 113 cm from the source, from the cone aperture of 37° the expected width of the background source is 240 cm, much wider than the ME0 size.

The profile disuniformity centered around strip 300 on the eta partitions 1 and 2 is due to the presence of a pillar in the GEM stack; the reduction in rate at the edges in the eta partition 1, instead, is due to the different length of the strips due to the different shape of the detector at low η , as the detector has a truncated trapezoid shape. The difference in the average rate among the three eta partitions is only due to the lower strip pitch at increasing

⁴The final ME0 back-end, the ATCA-based X2O board, does implement the readout of the s-bit path that will be used for the generation of the trigger primitives during Phase-2 operations.

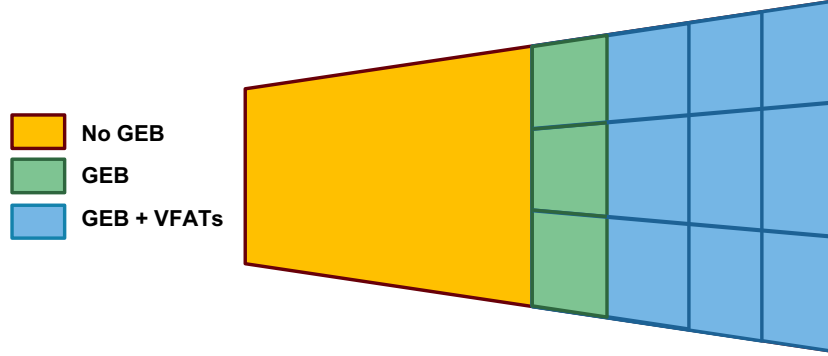


Figure 4.30: Readout scheme of the ME0 detector in the GIF++ test beam. The area not instrumented by a GEB is read out by a picoammeter to monitor the stability of the readout current.

η .

The average background rate on the ME0 as a function of the source attenuation is shown in Fig. 4.33. The trend follows closely the per-VFAT3 measurement; at equal flux, the ratio between the average rate per strip and the average rate per VFAT3 depends – besides on the number of active channels per VFAT3 – on the background cluster size.

At low source attenuations, the rate is linear, confirming that the attenuation factor is inversely proportional to the background flux; at high attenuation, however, the rate saturates to 1.3 kHz/strip. The non-linearity is due to the larger thickness of the attenuators: if the filter material is thick enough, the fraction of photons that interact non-destructively (e.g. by Compton processes) is not negligible and Lambert-Beer’s law cannot be applied.

4.5.5 Reconstruction and analysis

The reconstruction and analysis software uses the same tools developed for the analysis of the test beams in H4 (Sec. 3.5) with the updated geometry of the GIF++ setup.

Due to the presence of both a muon beam and an intense background conditions, the track reconstruction requires particular care to ensure proper identification of the muon hits. In the runs at highest background (absorption factor 1), the average rate of background hits in each tracking detector is $f = 25.6$ MHz: at VFAT3 pulse stretch 7, the probability of a muon event containing a background hit in a tracking detector is

$$p = \int_0^{(PS+1) \times 25 \text{ ns}} f e^{ft} dt = 0.993. \quad (4.7)$$

Considering that a single background signal together with a muon hit introduces two ghost hits in the tracking detector – due to the x-y readout layout –, the only way to ensure tracking without losing the vast majority of events is to reject spurious hits during the track reconstruction.

In presence of multiple hits in a tracking detector, then, the track reconstruction fits all possible tracks by obtaining all the possible combinations of hits; the track with the lowest χ^2

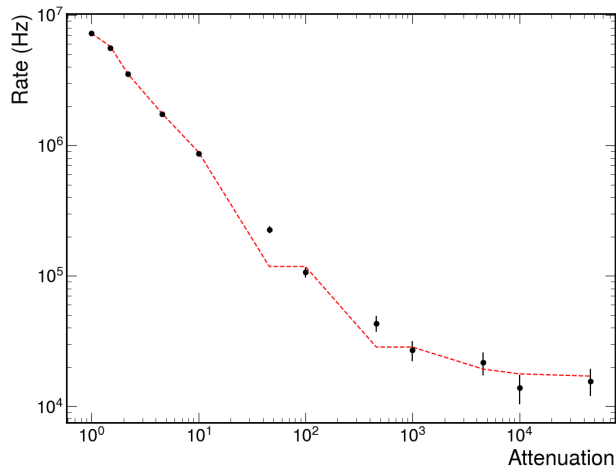


Figure 4.31: Total background rate as a function of the source absorption factor for tracking detectors measured with s-bits (red line) and DAQ path (black points).

is kept with all its corresponding rechits, while all the other hits in the tracker are discarded.

Fig. 4.34 shows the distributions of the χ^2 of the best track and of the discarded tracks in a low-background and in a high-background run (absorption factors respectively 10000 and 1); in both cases, the chosen tracks have χ^2 peaked at 1 and the average χ^2 does not change, showing that the track background rejection in the tracking is effective. The distribution of the rejected track χ^2 in both runs also peaks at 1, pointing to possible simultaneous muon tracks that are discarded in the reconstruction.

4.5.6 Efficiency measurement

The efficiency in presence of background is measured statistically to reject the muon contamination by background in the tracks.

Fig. 4.35 shows the residual distributions on the ME0 detector in two runs at high and low background (10000 and 1 absorption factor respectively); the distribution includes the residuals from the propagated track of all the hits in the events. Both distributions are fitted with the sum of a gaussian function and a linear function to model respectively the muon peak and the background.

The sigma of the gaussian is compatible in both cases. Fig. 4.36 shows the trend of the sigma of the residual peak as a function of the measured background rate, showing no observable dependency on the flux: this is a confirmation of the good performance of the tracking algorithm even with a large number of spurious hits. However, the sigma of the residual distribution is not a good estimation for the space resolution of the ME0 detector: no software tracking corrections have been applied to the tracking detectors, since the alignment of each of the two external detectors would require building a track with the remaining two tracking detectors only. Such tracks have a large propagation error, which does not allow a

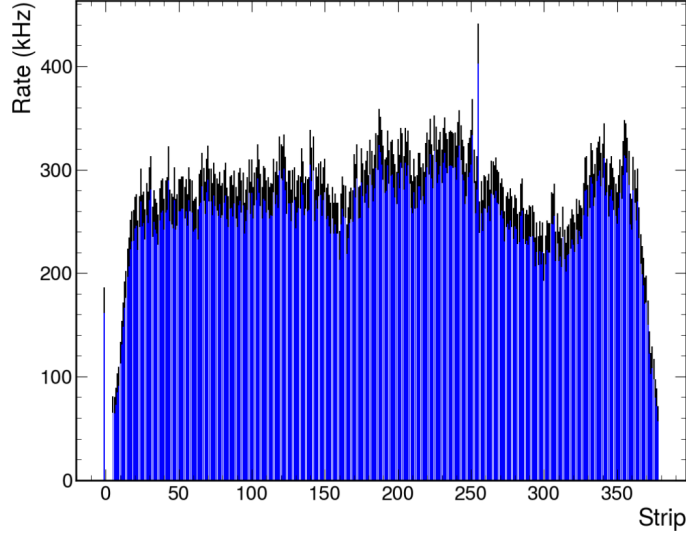


Figure 4.32: Rate profile measured on the ME0 detector at eta partition 8.

tracker alignment with precision better than the order of 1 mm; therefore, the uncertainty on the hit propagated to the ME0 is larger than the expected ME0 space resolution.

Due to the high contamination of background events, the efficiency cannot be measured event-by-event applying a cut on the residuals; therefore, the number of background hits falling within the residual cut is estimated from the sidebands and subtracted from the count of the matching hits.

To measure the efficiency statistically, we first define the two events:

- A = a muon hit is found compatible with an extrapolated track position within a residual cut x_c ;
- B = a background hit is found compatible with an extrapolated track position within a residual cut x_c .

Next we define the “measured efficiency” ϵ_m as the fraction of all events compatible with the extrapolated cut position within a residual cut x_c ⁵:

$$\epsilon_m = \frac{N\{|x - x_0| < x_c\}}{N_{\text{total}}} = P(A \cup B) = P(A) + P(B) + P(A)P(B),$$

where N_{total} is the number of tracks entering the detector surface and x_0 is the mean of the gaussian function. The two terms $P(A)$ and $P(B)$ are, respectively, the “true efficiency” ϵ of the detector and the “background contamination” b ; while the former is unknown, the latter can be calculated as the number of events with at least one hit in the sidebands between two cuts x_c and x_s , appropriately rescaled:

$$b = \frac{|x_c - x_0|}{|x_s - x_c|} \frac{N\{x_c < |x - x_0| < x_s\}}{N_{\text{total}}},$$

⁵Keeping into account the fact that the events A and B are independent, i.e. $P(A \cap B) = P(A)P(B)$.

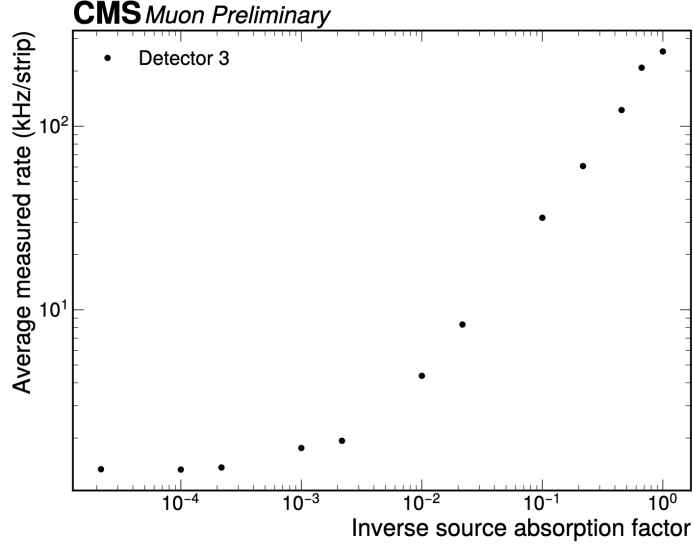


Figure 4.33: Average rate per strip on the ME0 detector as a function of the source absorption factor measured from the DAQ path.

where x_s is an arbitrary cut on the residuals used in the evaluation of the sidebands. By inverting the formula,

$$\epsilon = \frac{\epsilon_m - b}{1 - b}.$$

Fig. 4.37 shows the efficiency measured as a function of the residual cut for two runs at low and high background; the dashed red line is the *coarse efficiency*, i.e. the efficiency calculated without tracking information as the ratio between the number of events with at least one hit in the ME0 and the total number of events. In the low-background case, the tracking efficiency rapidly saturates after a cut of 2.5σ to a value close to the coarse efficiency; with high background, the saturation occurs to a much lower value because of the efficiency loss under irradiation, while the coarse efficiency does not yield a good efficiency estimation due to the background contamination.

4.5.7 Test beam data quality

Fig. 4.38 shows an efficiency scan with beam muons performed at the beginning of the test beam with no background. The efficiency is measured with tracking information and is shown as a function of the equivalent divider current and the effective gain; the efficiency plateau with muons at 96.3% is reached at gain 1×10^4 , while the nominal working point chosen for GEM detectors in CMS is 2×10^4 . By comparison with the gain drop under irradiation measured in the preliminary studies (Section 4.5.2), one can expect at the conditions of most intense irradiation at the GIF++ (255 kHz/strip or 2 MHz/sector) never to reach an effective gain below 1×10^4 , therefore never observing any loss of efficiency.

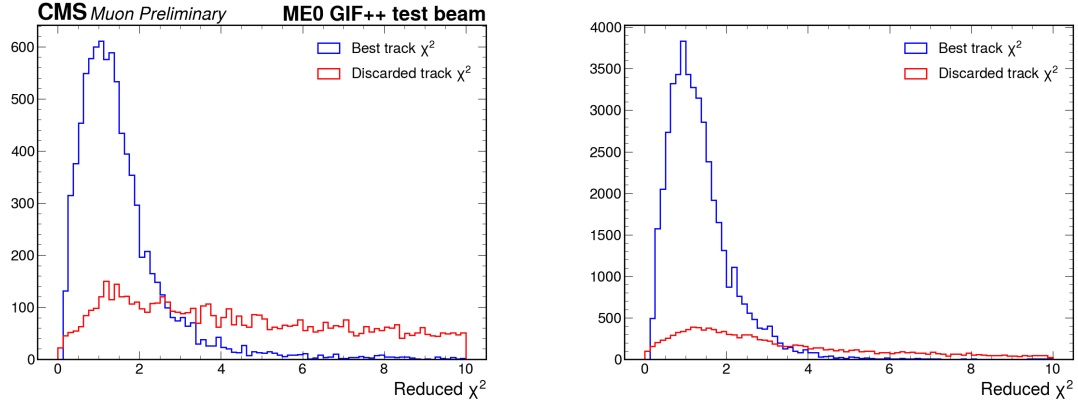


Figure 4.34: χ^2 of the best track per event and of the discarded tracks in a low background run (absorption factor 10000, left) and in a high background run (absorption factor 1, right).

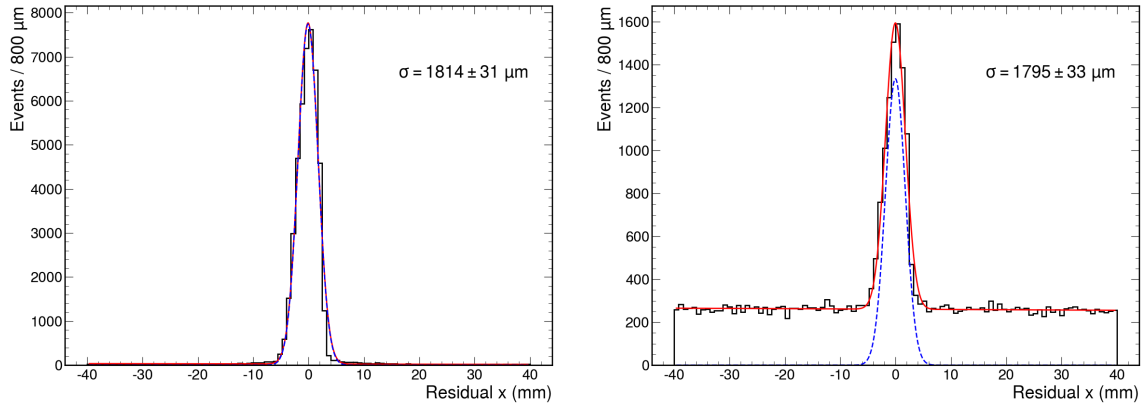


Figure 4.35: Track residual distribution on the ME0 for a low background run (absorption factor 10000, left) and for a high background run (absorption factor 1, right).

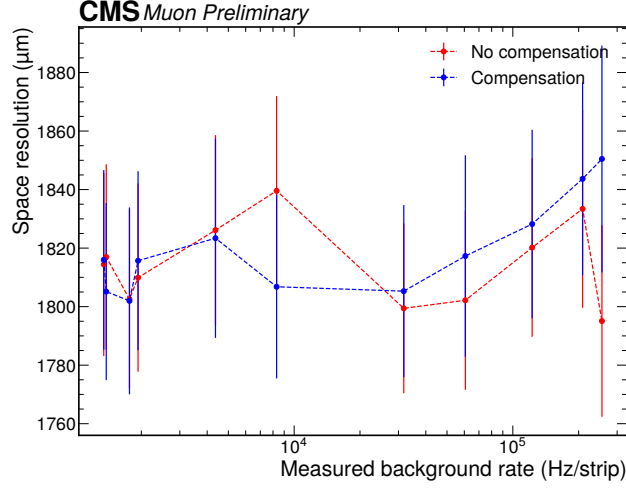


Figure 4.36: Trend of the sigma of the gaussian fit of the residual distribution as a function of the background signal rate.

The distributions of the cluster size in the ME0 for a low-background and a high-background runs are shown in Fig. 4.39. The muon and background hits are discriminated by a cut on the residual equal to 3σ . At high source attenuation, the average muon cluster size is 1.63, while the hits identified as background are highly contaminated by noise hits or secondary muons, lowering the average cluster size; conversely, at high background the average cluster size from source hits is 3.03 ± 0.01 , while the muon identification is highly contaminated by background hits. In all cases the most probable cluster size is 1.

The cluster size distribution has been measured for all background rates, as shown in Fig. 4.40; the measurement of the average muon cluster size is more precise at low fluxes, while for the background it saturates at low fluxes; the cluster size of both types of hits increases when the gain compensation is enabled, due to the higher effective gain, while the effect is not visible at low background rates because of the small increase in gain under compensation.

4.5.8 Test beam result: rate capability of the ME0 detector with final electronics

The measured efficiency to muons of the ME0 detector as a function of the background particle flux is shown in Fig. 4.41. The nominal gain is 2×10^4 and the high voltage filter resistor is 100 k Ω .

Differently from the expectations from the gain drop measurements, an efficiency drop is observable within the spanned range of background flux. Moreover, the efficiency is not recovered when the gain compensation is enabled, with a negligible difference between the two measurements; the efficiency loss observed at the maximum measured rate of 255 kHz/strip is of about 2.5% with respect to the nominal efficiency of 95%.

To quantify the loss of efficiency, a fit is applied to the rate capability curve with the

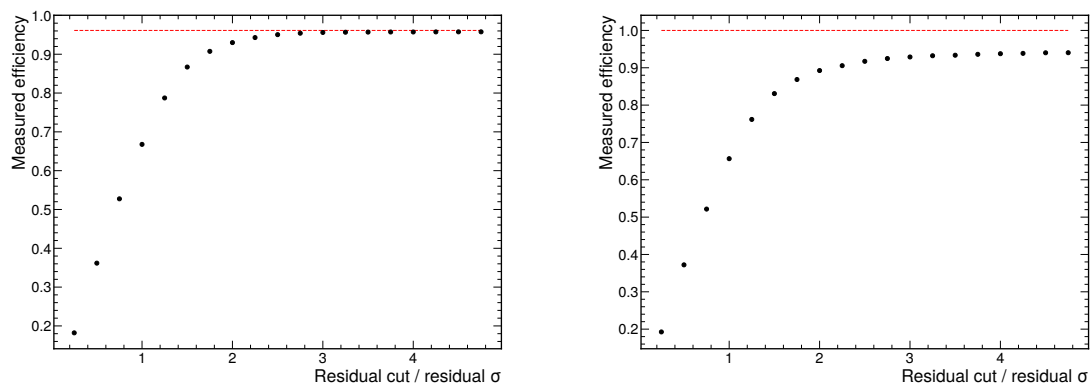


Figure 4.37: Measured efficiency of the ME0 detector as a function of the cut on the residuals in multiple of σ for a low and high background run (left and right). The red dashed line is the “coarse efficiency” calculated without tracking information.

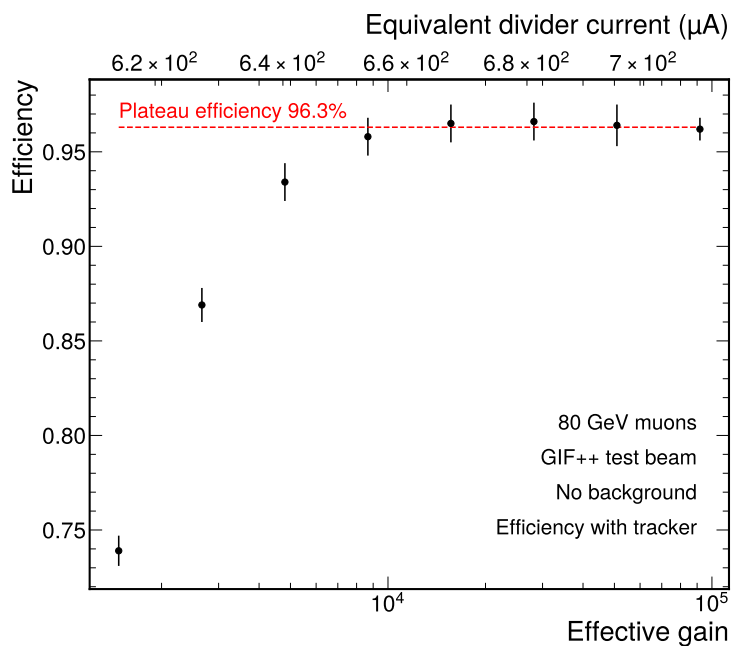


Figure 4.38: Efficiency scan of the ME0 detector in the GIF++ test beam as a function of the effective gain, with no background.

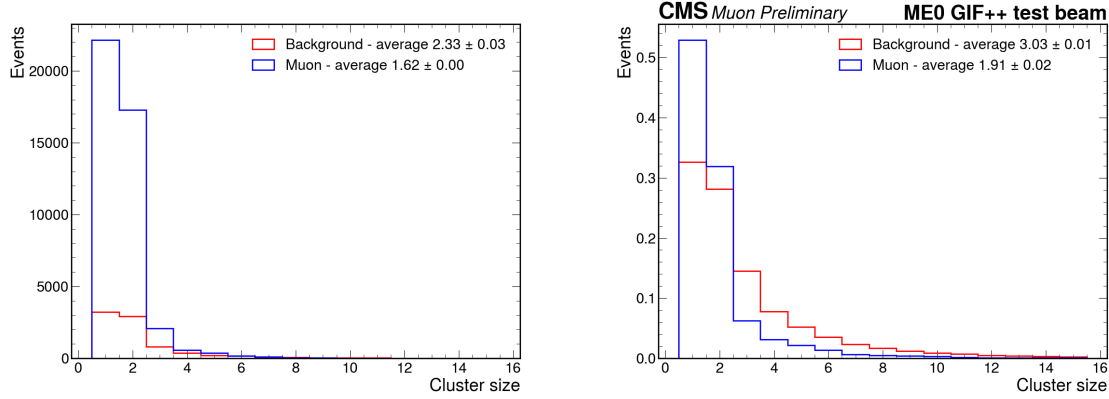


Figure 4.39: Cluster size distribution for a low background run (absorption factor 10000, top) and for a high background run (absorption factor 1, bottom). Muons and background hits are discriminated by the track matching with a cut on 2.5 times the σ of the residuals.

function

$$\epsilon = \frac{\epsilon_0}{1 + f\tau}, \quad (4.8)$$

where f is the measured background rate, and the fit parameters ϵ_0 and τ are respectively the efficiency without irradiation and the dead time of the system. A fit of the two rate capability curves yields a dead time of 141.2 ± 11.8 ns in absence of compensation and 90.7 ± 6.8 ns with gain compensation.

Model of the dead time. The fit of Eq. 4.8 can be obtained by considering the efficiency as the ratio $\epsilon = \nu/f$ between the average input rate of events f and the average observed rate ν ; due to the presence of the dead time, the probability of finding the system in a busy state (i.e. within a distance from the previous event lower than the dead time) is $p_{\text{busy}} = \nu\tau$, while the probability of the system to be free is $p_{\text{free}} = 1 - \nu\tau$. But the probability of finding the system in a free state is the efficiency itself, so:

$$\epsilon = \frac{\nu}{f} = 1 - \nu\tau \rightarrow \nu = \frac{f}{1 + f\tau} \rightarrow \epsilon = \frac{1}{1 + f\tau}. \quad (4.9)$$

The same identity can be also calculated considering the distribution of the event times for a Poissonian source is exponential with mean $1/f$: the measured rate ν is obtained as the mean of the distribution cut to values higher than the dead time:

$$\frac{1}{\nu} = \int_{\tau}^{\infty} fte^{-ft} dt = e^{-f\tau} \left(\tau + \frac{1}{f} \right) \sim \frac{1 + f\tau}{f}. \quad (4.10)$$

The origin of the unexpected efficiency loss can be searched among three of the components in the setup:

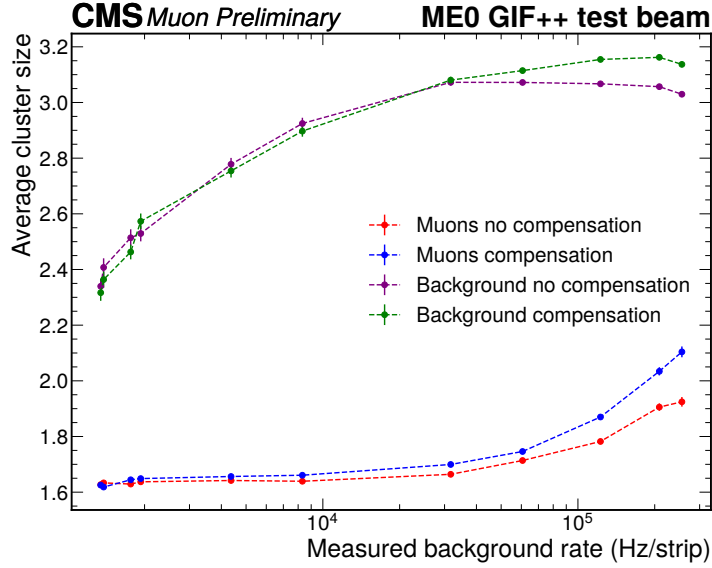


Figure 4.40: Trend of the average cluster size for muons and background hits as a function of the background rate.

- the intrinsic detector rate capability. If the gain drop under irradiation were higher than the one measured in the preliminary studies, the efficiency would be also lower; however, even an error of a factor two in the gain drop measurement would still show a visible difference in the efficiency between the no-compensation measurement and the case with compensation. Also the possibility that the gain compensation strategy be ineffective is unlikely, given the extensive tests performed both in laboratory and at the GIF++; both show the anodic current recover to the nominal value when the compensation is enabled. Furthermore, observation of the analog signal from a single strip with a linear preamplifier has showed that the spectrum of the signal amplitude recovers to the nominal average under compensation even at high background.
- the offline reconstruction in high background. If the performance of the tracking algorithm were ineffective in presence of many background hits, the efficiency might be underestimated; however, the reconstruction software has been tested to ensure its reliability with several fake hits per event, as shown from the average track quality and by the residual distributions which are not influenced by the background. The analysis has also been repeated by selecting only the events with no spurious hits, obtaining the same efficiency severely with reduced statistics.
- the read-out electronics. Among the front-end components that could be responsible for the dead time, the VFAT3 ASIC is quoted for a rate capability higher than 2 MHz/strip, at least one order of magnitude higher than the rates reached at the GIF++, while the digital electronics (made of the lpGBT and the VTRX+) is considered reliable up to

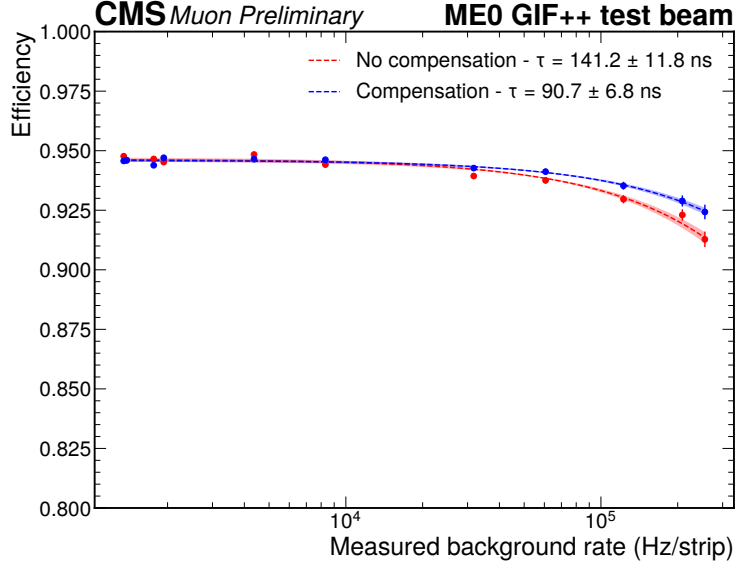


Figure 4.41: Efficiency of the ME0 detector as a function of the background rate, with and without voltage compensation. The curves are fitted with the function in Eq. 4.8.

bandwidths of the order of the Gpbs. Nonetheless, the readout electronics is the only component of the setup never tested thoroughly against high rates with the final detector.

The following section summarizes the triple-GEM rate capability measured with final electronics to reproduce the GIF++ test beam findings and determine the cause of the efficiency loss.

4.6 Rate capability with final electronics under x-ray irradiation

A rate capability measurement on a triple-GEM detector with CMS front-end electronics was performed in laboratory using an x-ray tube to extract the dead time of the VFAT3. The nominal rate capability of the VFAT3 by specification is 2 MHz per strip; this value was tested during the first proof-of-performance of the ASIC using the VFAT3 CBM unit, by injecting a calibration pulse in a single front-end channel and counting the output signal rate. The rate capability was defined as the maximum input rate at which the measured rate was linear.

One possible flaw in the measurement is that the input calibration signal is a square waveform or a fast pulse, depending on the programmed charge injection mode: the signal duration can be adjusted between 1 and 8 BXs (up to 200 ns), but the rise and fall times are faster than the analog signal of a GEM detector. To repeat the measurement with a more realistic signal, at first a bench test was performed with a waveform generator programmed to emulate the signal shape of a GEM detector.

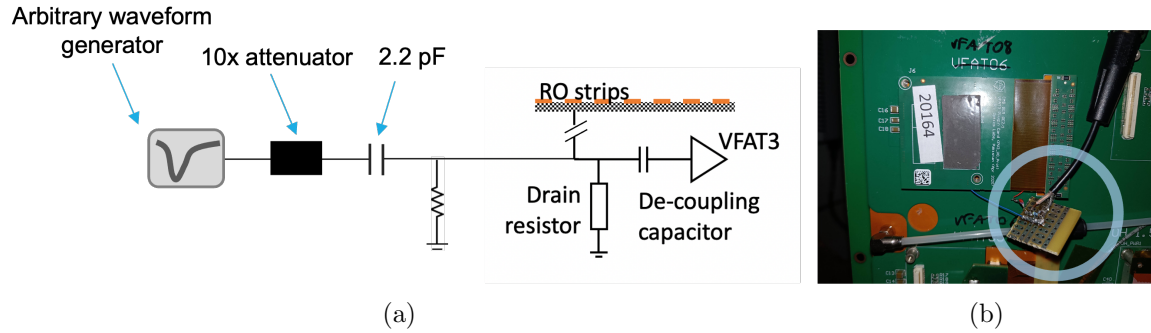


Figure 4.42: (a) Connection scheme for the rate capability measurement of the VFAT3 with external pulse generator. (b) Picture of the VFAT3 with the soldered CR filter and connection to the external pulse generator.

4.6.1 Dead time measurement with pulse generator

The external calibration pulse setup for the dead time measurement is shown schematically in Fig. 4.42a: the tested chip is a plugin card read out by a GE2/1 OptoHybrid. One of the channel strips was soldered to the output of a waveform generator through a $10\times$ attenuator voltage attenuator and a CR circuit made of a 2.2 pF capacitor and a $100\text{ k}\Omega$ resistor two ground; a picture of the setup is shown in Fig. 4.42b.

The amplitude of the generated pulse was set to 100 mV to obtain a current signal at the CR output of charge $10\text{ mV} \times 2.2\text{ nF} = 22\text{ fC}$; the signal shape was programmed for a rise and falling time of respectively 24 ns and $1\text{ }\mu\text{s}$, to obtain a current pulse at the channel input with a negative signal of 24 ns duration (close to the GEM signal duration) and a negligible positive overshoot of $1\text{ }\mu\text{s}$.

The input signal rate was increased up to 1 MHz , the highest allowed by the generator, and the VFAT3 counting rate was measured from the OptoHybrid s-bit counter while masking out all channels except for the tested one. Fig. 4.43 shows the resulting linearity curve fit with a saturating function of the form:

$$\nu = \frac{f}{1 + \tau f}, \quad (4.11)$$

where f is the input pulse rate, ν is the measured s-bit rate and the fit parameter τ is the dead time.

The observed rate linearity is close to 1; although the measurement did not reach the nominal rates of saturation of the chip, it also failed to reproduce the dead time observed in the GIF++ test beam, for which a loss of linearity would be expected for a input rate of a few hundreds of kHz.

4.6.2 Dead time measurement with x-rays

A rate capability measurement with a more realistic setup has been performed with a triple-GEM detector irradiated with x-rays and read out by the final front-end electronics.

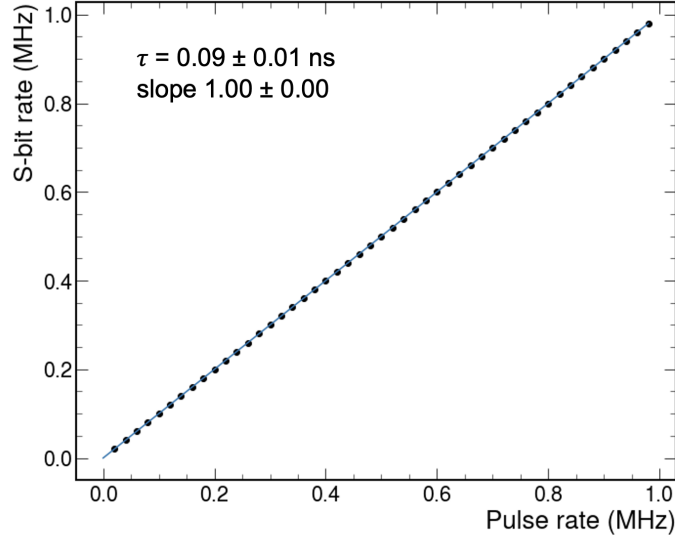


Figure 4.43: S-bit rate of the VFAT3 as a function of the input rate for a signal generated with a waveform generator.

Fig. 4.44 shows the setup: the tested detector is a $10 \times 10 \text{ cm}^2$ triple-GEM read out by four VFAT3 hybrids, in turn connected to a GE2/1 GEB and to a CVP-13 backend. The goal of the measurement was to measure the dead time of the entire system by observing the saturation in the measured signal rate per strip as a function of the x-ray flux. The x-ray gun is a 4 W Amptek Mini-X powered with an increasing current between 5 and $100 \mu\text{A}$ and at a fixed voltage of 40 kV; as in the first rate capability measurements described at the beginning of this chapter, the signal spectrum of the detector consists mostly of the 8 keV fluorescence peak of the copper in the cathode. Before the measurement, the linearity of the x-ray flux as a function of the x-ray power was ensured by placing a set of copper attenuators between the source and the detector itself, in order to strongly attenuate the output flux; no deviations from the expected linearity were observed.

The dead time of the system was measured strip-by-strip from the trend of the signal rate as a function of the x-ray gun current; the rate was measured from the DAQ path with a cyclic trigger, using the same technique as in the GIF++ test beam, and calculated from Eq. 4.6. The rate trend was fitted with Eq. 4.11 to extract the channel dead time. The gain compensation of the detector was always enabled to ensure the measurement was not influenced by the detector intrinsic rate capability.

Fig. 4.45 shows an example of the rate trend on each of the four VFATs in the setup as a function of the x-ray current; the trend clearly shows the signal rate saturating at 2.5 MHz for all VFATs. The difference in rate between the different curves is due to the non-uniform irradiation of the detector.

A distribution of the dead times for all four VFATs is shown in Fig. 4.46. The average dead time is 355 ns with an RMS of 48 ns; the precision of the measurement on VFATs 0 and 5 is lower than VFATs 3 and 9 because they read out the y strip plane, which has a lower

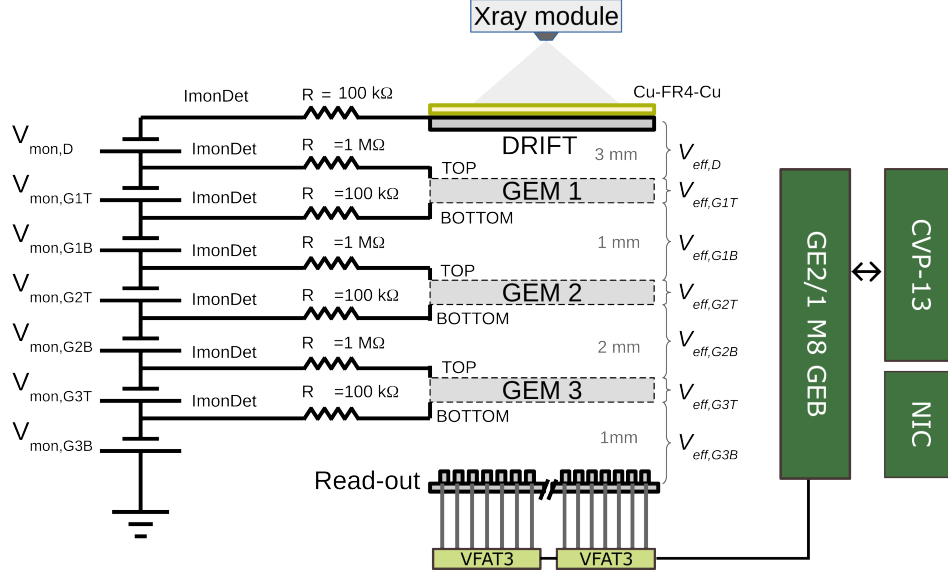


Figure 4.44: Setup for the rate capability measurement with x-rays and final electronics.

efficiency than the x plane.

The result has been reproduced also with a full simulation of the VFAT3 circuit [74]: when two input pulses are sent closer in time than some time τ_{sim} , the VFAT3 discriminator outputs a single pulse (Fig. 4.47). This observation traces the issue to the recovery time of the comparator. The simulation was repeated for a variable input charge of the first signal, as shown in Fig. 4.48; the dead time was found to be increasing logarithmically with the input charge.

4.6.3 Comparison with detector dead time

The x-ray measurements, confirmed by simulations, show that a visible efficiency loss appears under irradiation due to the dead time of the front-end ASIC. Measurements performed in a test bench with no particle source – such as the external pulse generator test described above and the internal pulse injection test performed in the early VFAT3 performance assessment – do not observe an efficiency drop at rates lower than 2 MHz because they are all performed with a cyclic pulse, with a fixed time between two consecutive input signals; in a natural source, the time between two consecutive events usually follows an exponential distribution, so the probability of two events occurring closer than the dead time τ is $\int_0^\tau f e^{-ft} dt = 1 - e^{-f\tau} \sim f\tau$. As a consequence, the 2.5 MHz/strip design limit is not the ASIC rate capability, but its saturation rate; the actual rate capability of the VFAT3, defined as the signal rate at which the efficiency drops by 10%, is 280 kHz/strip.

However, the VFAT3 dead time as measured and simulated is larger than the 90.7 ± 6.8 ns measured in the GIF++ test beam – even when accounting for a possible dependence on the input charge. A simple toy monte carlo simulation has been developed to understand how a dead time of about 300 ns per strip can give rise to a measured detector dead time of 100 ns.

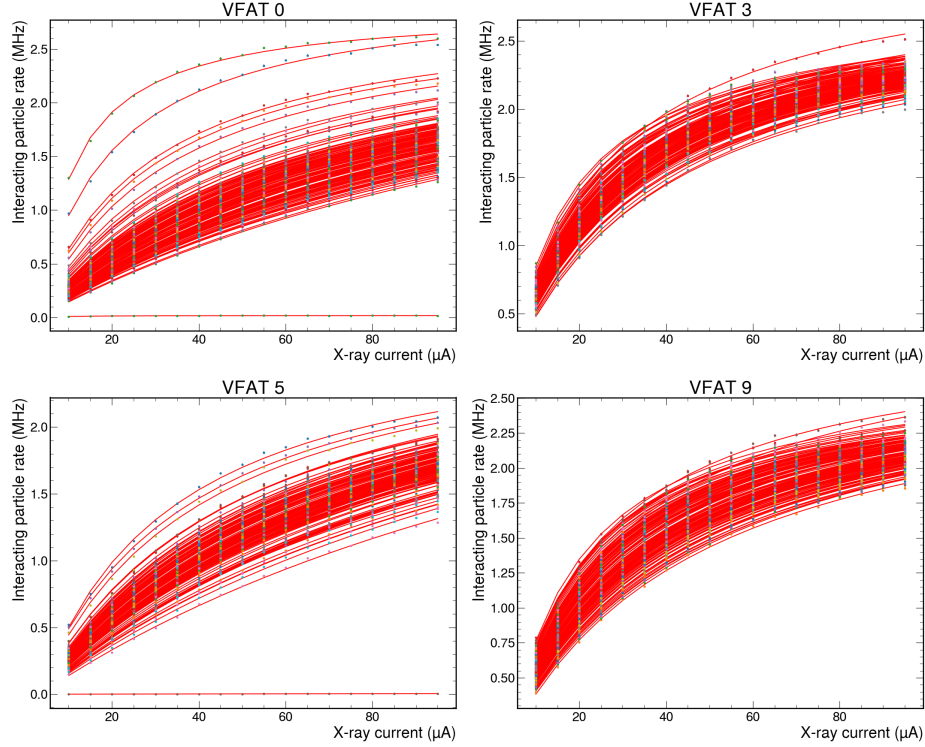


Figure 4.45: Rate per channel on each of the four VFATs in the setup as a function of the x-ray gun current, fitted with a saturating function for the extraction of the dead time.

The details of the simulation are shown in appendix B; the outcome of the simulation shows that, due to the finite cluster size of the background hits, the detector dead time is lower than the “per-strip” dead time of the front-end electronics; this reconciliates the two results at least qualitatively.

4.7 Outlook on the performance of the ME0 detector

The observations of the GIF++ test beam confirmed with x-rays prove that the rate capability of the ME0 detector is not limited only by the gain loss due to the resistive effect, but also by the dead time of its front-end electronics. The GIF++ findings can be related to the expected efficiency loss of ME0 in the operations at LHC by comparison with the background simulations.

The highest expected background flux in ME0 in Phase-2 is 200 kHz/cm^2 . The azimuthal segmentation of the GEM foil allows to limit the average rate per sector to 1.6 MHz, with small sector-by-sector variations; comparison with both laboratory measurements with x-rays and GIF++ on the intrinsic detector rate capability foresee a negligible efficiency loss under irradiation for the HL-LHC fluxes, with an effective gain under irradiation not lower than 10^4 . The availability of the gain compensation procedure, confirmed in both setups, will be

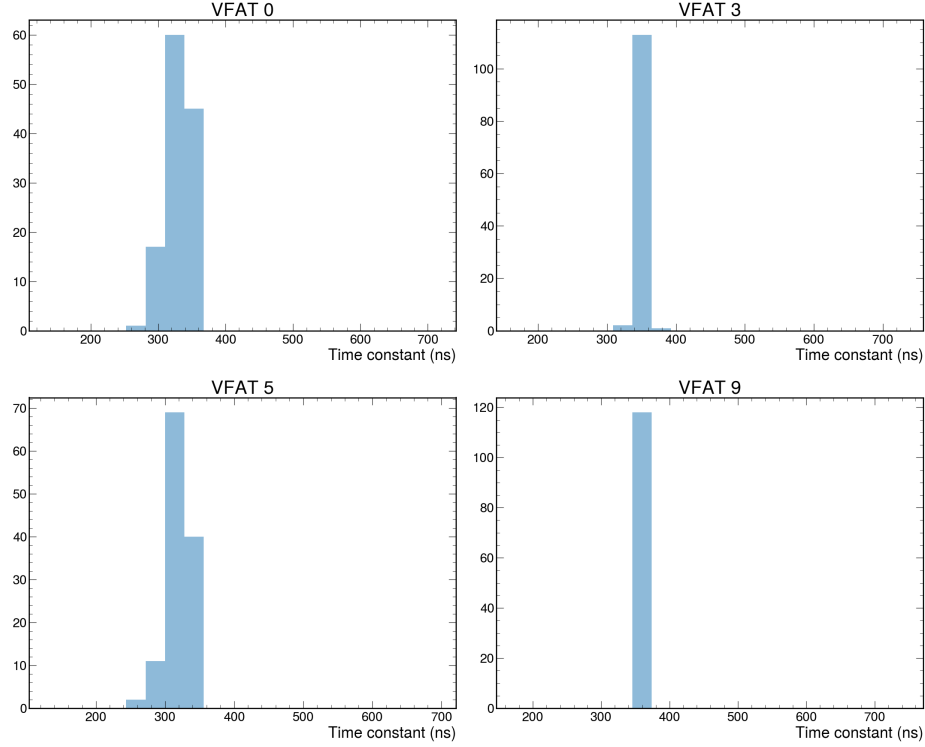


Figure 4.46: Dead time distribution of all front-end channels, grouped for each VFAT.

anyway a reliable mitigation strategy in case of higher drops than expected.

The efficiency drop due to the dead time of the front-end, instead, will be most evident in the highest-pseudorapidity readout sector, where the expected background particle rate is 28 MHz. The expected background rate per strip is then $f_{\text{strip}} = f_{\text{sector}}/n_{\text{strips}} \times \text{cluster size} = 73 \text{ kHz/strip} \times \text{cluster size}$. There is currently no simulated value of the cluster size for the background in ME0; a reasonable guess between 2 and 3 gives an expected rate between 146 and 219 kHz/strip, for an efficiency loss between 2 and 2.5% – in addition to the average efficiency limit to 94-96% due to the dead area of the GEM foil segmentation (see Tab. 3.5). The theoretical maximum efficiency for segment reconstruction, assuming at least 4 out of 6 detector layers are needed to reconstruct a segment, is 99% for a single-layer efficiency of 92%.

For these reasons, the efficiency loss due to the rate capability is not likely to have a visible impact on the performance of the ME0 detector. However in a possible prosecution of the ME0 rate studies it is essential to know precisely the effective efficiency loss, which still depends on several parameters known with large uncertainty:

- the exact values of the background fluxes, which are subjected to change according to the design changes of the rest of the detector (shielding and HGAL design included), simulation refinements and instantaneous LHC luminosity;

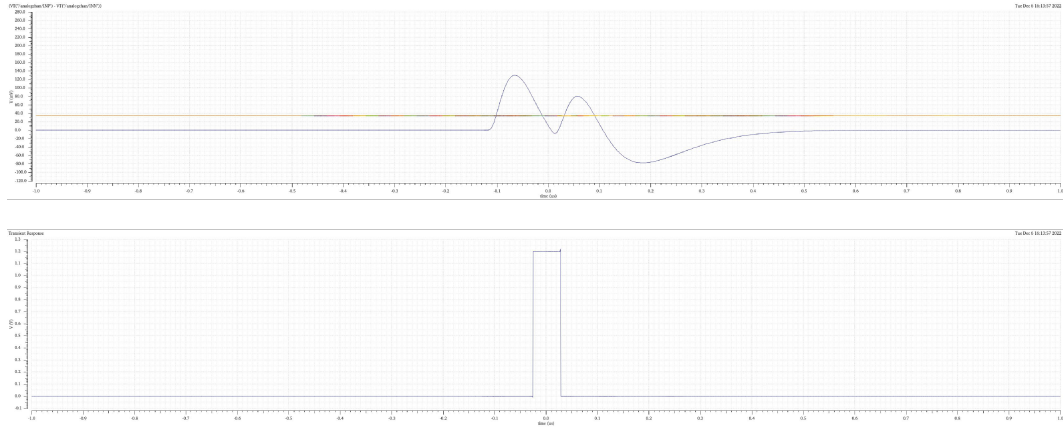


Figure 4.47: Simulated VFAT3 arming comparator response to two close input signals. On top, two simulated input signals with arrival time distance 100 ns; on the bottom, output signal from the comparator. The yellow horizontal line represents the comparator threshold. Simulation by [74].

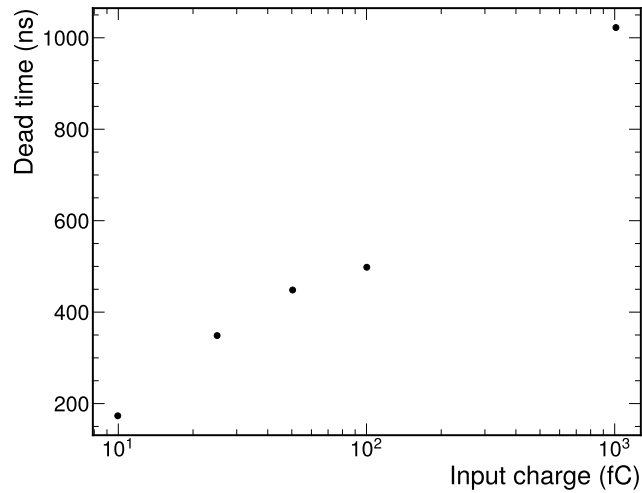


Figure 4.48: Simulated dead time of the VFAT3 as a function of the input charge of the first signal, for a fixed input charge of the second signal of 10 fC [74].

- the response of the detector to the background, including the cluster size of the background hits;
- the response of the front-end electronics to highly ionizing particles: preliminary simulations of the VFAT3 analogic part show a dependency of the dead time on the input charge, with dead times higher than 1 μ s for signals released by highly ionizing particles.

4.8 Conclusions

An R&D campaign for the design optimization of the triple-GEM detectors for the ME0 system has been pursued. ME0 will be the large-area station instrumented by an MPGD technology with the highest background flux in an high-energy physics experiment; the first challenge is posed for the intrinsic detector rate capability, which is reduced under large-area irradiation by the presence of the discharge protection circuits. Measurements with x-rays on triple-GEM prototypes have ensured good performance with controllable gain losses up to fluxes of 2 MHz per foil sector, and a voltage compensation procedure has been extensively tested to ensure recovery of the gain drops; the GEM foil layout has been redesigned with an azimuthal segmentation with respect to the LHC beam line, to minimize the gain drop and make it uniform over the entire detector surface. The new design has been validated with x-rays and with uniform irradiation at the GIF++ at CERN in the near-final detector design, including the effect of the high-voltage filter.

The second rate limitation in the ME0 detector, emerged in the GIF++ test beam, lies in the front-end electronics, which showed a limited rate capability due to a dead time in the analogic circuit of the VFAT3 ASIC. The GIF++ test beam showed an efficiency loss up to 2.5% due to the dead time of the VFAT, later confirmed with x-ray irradiation to be slightly lower than 400 ns. The impact of the electronics dead time on the ME0 performance is expected to stay mitigated by the 6-layer structure of the ME0 station, with a foreseen efficiency in the highest- η region of 92% of a single ME0 layer and of at least 99% of the entire stack; to the present knowledge, the ME0 technology is suitable for high-rate operations at the HL-LHC and its physics performance is expected to be unaffected. However, confirmation of this projected performance is needed in the parameters with the highest uncertainty, both in the detector performance (such as the dependency of the VFAT3 dead time from the input signal charge) and in the ME0 environment during the HL-LHC phase (such as the final CMS design and the background cluster size).

Chapter 5

Fast timing MPGD

The present chapter describes the development and tests performed on a prototype of fast timing MPGD (FTM), a detector designed with the purpose of improving the time resolution of traditional MPGDs while maintaining high space resolution and rate capability. The FTM principle was born together with the rise of resistive micro-pattern gaseous detector from the idea of extending the working principle of multi-gap RPCs to the MPGD domain.

The development of this technology poses several challenges in terms of material choice, production techniques, physics simulation and readout electronics; the goal of my activity on the FTM is to formulate from the tests on the most recent FTM prototype, along with the history of the previous measurements, a list of constraints to guide the future R&D and get an outlook on the possible performance reachable in the future.

5.1 Fast timing applications

Applications of precise timing are under investigation in high-energy physics experiments both for next-generation colliders and for the high-luminosity LHC era. The attractiveness of fast timing detectors lies in their potential for pile-up mitigation using four-dimensional vertex reconstruction in high-luminosity scenarios. Among the applications outside high-energy physics, precise timing can improve the position resolution through time-of-flight measurements, which has potentials in the development of more affordable imaging systems to be used in medical diagnostics, earth physics or homeland security.

5.1.1 Fast timing in high-energy physics experiments

Several present-generation high-energy physics experiments use or plan to use in its upgrades fast-timing detectors for four-dimensional vertex reconstruction (such as the ATLAS high-granularity timing [75]) or for particle identification (such as the ALICE TOF system [76]). As a realistic application case of fast timing we consider the MIP timing detector (MTD), a new subdetector of the CMS experiment whose installation in the CMS apparatus is planned before the beginning of the HL-LHC era [77]. The MTD will be a hermetic detector placed between the CMS tracker and the calorimeters and will be instrumented by LYSO crystals read

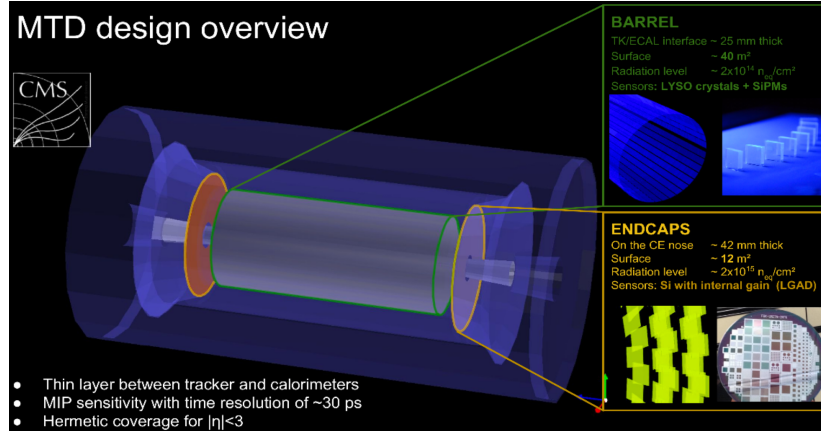


Figure 5.1: Overview of the CMS MTD, from the MTD technical design report [77].

out by silicon photomultipliers (SiPMs) in the barrel and low-gain avalanche photodetectors (LGAD) in the endcap, with a declared time resolution between 30 and 40 ps and a space granularity between 3 mm² and 1 cm². The schematic geometry of the MTD is shown in Fig. 5.1.

The goal of the MTD will be the time-tagging of charged particles crossing the CMS detector. In the ultimate high-luminosity LHC scenario, the collider instantaneous luminosity will reach $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with an expected pileup of 200 collisions occurring with a time spread of 180 to 200 ps. The offline event reconstruction, based on the particle flow algorithm, is not able to cope with such high background, in particular with an expected increase in the mis-identification of the primary vertex; the addition of timing information will allow slicing the event in 30 ps windows, thus recovering the same event reconstruction performance as the one maintained during Phase-1. A comparison of the vertex reconstruction from simulations with and without timing information is shown in Fig. 5.2.

The impact of the MTD on the CMS performance is essential especially for physics channels involving isolated photons or leptons and extended objects or global quantities such as jets or missing transverse energy. Measurements such as the Higgs self-coupling will benefit from the improved signal yield in decays such as $HH \rightarrow b\bar{b}\gamma\gamma$ or $HH \rightarrow 4b$, while search for several BSM phenomena will be aided by the improved missing transverse energy resolution.

5.1.2 Fast timing application outside high-energy physics

Outside physics instrumentation at present or future colliders, the improvement of timing precision in all kinds of particle detectors is being pursued for application such as medical diagnostics, with famous examples such as positron emission tomography (PET).

PET is a monitoring technique used especially for tumor diagnosis in which the region interested by the illness is localized from the emission of pairs of photons by electron-positron annihilation; the vertex of the two photons is reconstructed from the intersection of different lines-of-response (LOR) over several events. With the addition of timing information sufficiently precise to measure the time-of-flight of the photon pair, an additional spatial coordinate

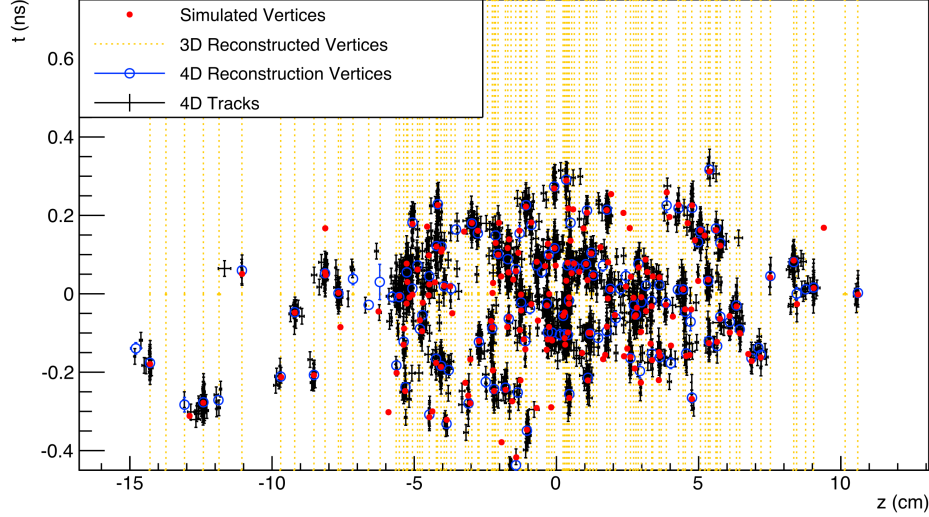


Figure 5.2: Simulated vertex position and creation time in an LHC bunch crossing with pile-up 200. The vertical yellow lines represent the identified vertices using spatial information only, while the error bars on the dots represent the vertices discriminated using timing information with a 30 ps resolution [77].

along the LOR is available for the vertex reconstruction (Fig. 5.3). PET with time-of-flight (TOF-PET) has the potential to simplify the diagnostic procedure by reducing the cost of the detector and to increase the safety of the procedure by reducing both the time of the exposure and the amount of administered radiopharmaceutical; the same principle could be applied to other scintillography devices for applications such as homeland security and laser imaging detection such as systems used in self-driving cars (LIDAR).

State-of-the art detectors used for time-of-flight measurements typically rely on fast scintillators, which can deliver time resolutions of the order of a few hundreds of picoseconds. The ongoing effort is mostly aimed at reaching time resolution of the order of 10 ps, which could translate to space resolutions of few mm when using the timing information alone [78]. Developments toward 10 ps timing with scintillators are focused on improving the light yield and optimizing collection efficiency of the crystals and the precision of the readout electronics, as well as developing faster scintillators through doping; a parallel line of development instead consists of maintaining the good time performance of present-generation detectors while reducing the cost by replacing solid-state detectors by less expensive technologies, such as gaseous detectors. This justifies the fast timing challenge with detectors of time resolution of hundreds of picoseconds such as multi-gap RPCs; a fast timing MPGD would also be able to combine good timing information with low space resolution.

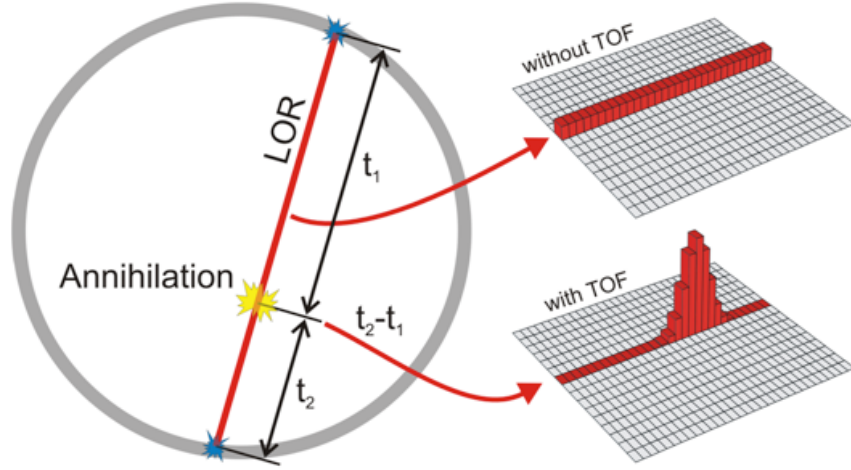


Figure 5.3: Schematic of the line-of-response (LOR) reconstruction in PET; in presence of time-of-flight information with a resolution of a few hundreds of ps, the vertex position along the LOR can be determined with a precision of the order of cm.

5.2 Fast timing in gaseous detectors

The first MPGDs to be invented, as well as the most consolidated ones in the major high-energy physics experiments, share a geometry that divides the active volume in a drift and an amplification region. This common scheme, together with an effective gain that can generally go no higher than 10^4 , sets a limit for the time resolution of a classical MPGD; the timing optimization of a traditional MPGD and possible modifications to overcome its limit are discussed in the following sections.

5.2.1 Intrinsic time resolution of classical MPGDs

The main theoretical limit of the time resolution of an MPGD to MIPs is the fluctuation in the distance from the amplification region of the last cluster of primary ionization.

The readout signal in a detector is the sum of the signals generated by all the primary ionization clusters released by the MIP in the drift gap; the first part of the signal rising edge is induced by the last cluster created in the drift gap, since it is created closest to the multiplication region and so it is the first one to reach it.

The number of clusters per unit length released by a MIP in the drift gap follows a Poisson distribution with some mean λ ; consequently, the distance between the beginning of the amplification region and the position where a cluster is created is exponentially distributed with mean position λ^{-1} :

$$p(x|\lambda) = \lambda e^{-\lambda x}, \quad (5.1)$$

while the time between the creation of the cluster and its arrival to the amplification region

is $t = x/v_d$ (where v_d is the drift velocity) and is still exponentially distributed:

$$p(t|\lambda) = p(x(t)|\lambda) \frac{dx}{dt} = \lambda v_d e^{-\lambda t v_d}. \quad (5.2)$$

The square root of the variance of this distribution, $\sigma_t = (\lambda v_d)^{-1}$, is the expected contribution of the primary ionization statistics to the detector time resolution. The remaining path of the cluster during the charge multiplication follows a Poisson distribution with mean $(\alpha \lambda v_d)^{-1}$, where α is the Townsend coefficient, and gives a negligible effect to the time resolution in a traditional detector.

5.2.2 Timing optimization in MPGDs

The two main hypotheses in the simplified model described above – that the first part of the signal leading edge is always created by a primary ionization cluster in a drift gap and that the readout electronics is always able to determine the event time from the rising edge of the anode signal – leave space for several optimizations of the design to improve the detector timing.

Some exemplar design choices that do not drastically change the detector geometry are those adopted for the triple-GEM detectors of the LHCb experiment (see 2.2.2) [61]:

- the reduction of the first transfer gap from 2 to 1 mm, which suppressed the formation of primary ionization clusters delayed from those created in the drift gap;
- the reduction of the induction gap, again from 2 to 1 mm, which decreased the signal rise time with an improvement of the electronics timing;
- the use of CF₄-based mixtures, which increased the drift velocity and consequently the intrinsic time resolution (Fig. 5.2).

The LHCb layout allowed reaching a time resolution below 5 ns [61] – with improvement in the muon trigger capabilities against the 10 ns resolution of the previously more consolidated design – and later inspired the detector design of other experiments such as CMS.

Larger improvements in the time resolution require a deeper redesign of the detector structure. Possibly the most successful example has been the PICOSEC-MicroMegas [79] detector, whose principle is based on reducing the position of primary ionization to a single point. A PICOSEC detector is a MicroMegas detector in which the cathode is made of a high-quantum efficiency material (such as CsI or B₄C) and coupled with a Cherenkov radiator; primary photoelectrons are produced at the passage of a MIP via photoelectric effect by the Cherenkov light, while the thickness of the drift gap is reduced to a few hundreds of μm to suppress the primary ionization in the gas. The main contribution to the PICOSEC time resolution is the fluctuation in the drift time of the primary electrons [80] which can be limited by operating the detector at a high enough drift field to achieve a “preamplification” of the order of 100 before the electrons reach the mesh; at the same time, at low primary charges of the order of a few electrons the amplification region can operate at a high gain (of the order of 10^5). MicroMegas are known to exhibit a very fast single-electron response [81];

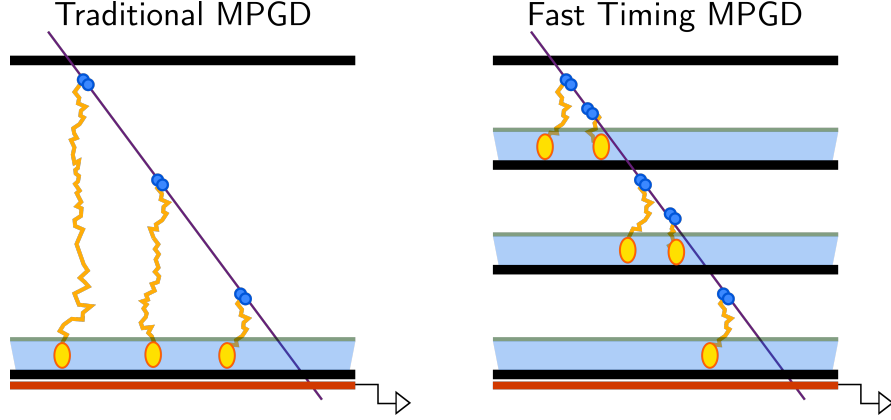


Figure 5.4: Layout of a traditional MPGD (left) compared with that of an FTM (right). The blue regions represent the amplification layers and the yellow blobs represent the avalanche.

with such detector layout, time resolutions of few tens of picoseconds have been measured for a single photoelectron, while timing below 20 ps has been measured with MIPs [82]. Its excellent timing performance makes the PICOSEC detector a candidate for applications as a MIP timing layer over moderate areas at future experiments, for example the Muon Collider; present R&D is oriented to optimization of the photocathode robustness, cost and lifetime in high rates and scaling to larger area and finer readout granularity.

5.2.3 Working principle of the fast timing MPGD

In the FTM layout, the gas active volume is divided in several independent layers, each with its own drift and amplification regions (Fig. 5.4); assuming the signal from each layer is induced on a single external readout region, the rising edge of the signal is now determined by the first cluster reaching the amplification region in *any* layer. If x_i is the distance from the amplification region of the last cluster created in the i -th layer, the signal arrival time is determined by the fluctuations in the variable $x = \min\{x_1, \dots, x_n\}$. From Eq. 5.1 one obtains¹ that the position x follows the distribution

$$p(x|\lambda) = N\lambda e^{-N\lambda x}, \quad (5.3)$$

where N is the number of layers. As a result, the contribution of the drift fluctuations to the time resolution is $\sigma_t = (N\lambda v_d)^{-1}$ and the time resolution is expected to decrease linearly with the number of layers².

The model is confirmed by a simple Garfield simulation [83]. For a two-layer detector operated in Ar:CO₂ 70:30 ($\lambda = 31 \text{ cm}^{-1}$), with an electron drift velocity of 7 cm/ μs (obtained

¹Using the property that the minimum of a set of independent identical exponentially distributed random variables is also exponentially distributed.

²This is an improvement with respect to a timing information obtained as the average of the time stamps of all layers, in which case the time resolution would be $\sigma_{\bar{t}} = (\sqrt{N}\lambda v_d)^{-1}$.

at a drift field of 3 kV/cm) the expected time resolution is 2.3 ns; sub-ns time resolutions would require at least four layers.

Two essential aspects lie at the basis of the working principle of the FTM and have shaped both past and ongoing directions of its development:

- the structure must be electrically transparent to signals generated in each layer, to allow the readout from external electrodes;
- each layer must be made of a compact amplification structure able to reach high multiplication, due to the small drift regions.

The two requirements can be satisfied with a resistive detector: electrodes with high resistivity on one hand must be used to ensure signal transparency and on the other are at the basis of several MPGD technologies with high amplification and intrinsic spark protection.

5.3 History of the FTM

The FTM concept was formulated in 2015 [84]. The first FTM prototype was assembled at CERN soon after, with the purpose of proving the signal transparency to multiple layer and demonstrating its working principle with charged particles. The prototype geometry is shown in Fig. 5.5: the detector was made of two layers, each delimited by two electrodes in resistive kapton (drift and anode); the amplification area was made of a 50 μm thick kapton foil covered on top by a 100 nm layer of DLC (diamond-like carbon). A single circular copper pad placed on the bottom acted as readout electrode, while the drift electrode of the top layer was made of copper instead of resistive material to be used as a second readout pad; the total active area was about 20 cm^2 and each drift gap had a thickness of 250 μm .

The prototype was first irradiated with x-rays, reading out the signal both from the bottom pad and the top drift with an Ortec 142PC charge-sensitive preamplifier with integration times of the order of 1 μs ; signals were observed simultaneously in both electrodes with good linearity of rate, suggesting good signal induction between each of the two layers and the two readout electrodes [86]. In a test beam at the CERN North Area, a time resolution of 2.4 and 1.9 ns was measured respectively with muons and pions, in agreement with the expected time resolution for two layers in Ar:CO₂ 70:30 [85]. However, the total efficiency of the detector was lower than 20%, against an efficiency of 80% expected for a total drift thickness of 500 μm ; this observation suggested either of two possibilities:

- the amplification of the foils was too low to detect all primary ionization clusters;
- the avalanche in the top layer did not induce any signal on the readout pad.

In the former case, the time resolution was biased by the fact that the events detected were those with higher primary charges; in the latter, the time resolution measured was not due to the competition between the two layers, but only to the small thickness of the drift gap in the bottom layer, that reduced the fluctuations in the arrival time of the primary cluster.

To increase the efficiency and investigate the signal induction issues, a second FTM prototype instrumented with four layers and an amplification foil based on a resistive Thick GEM

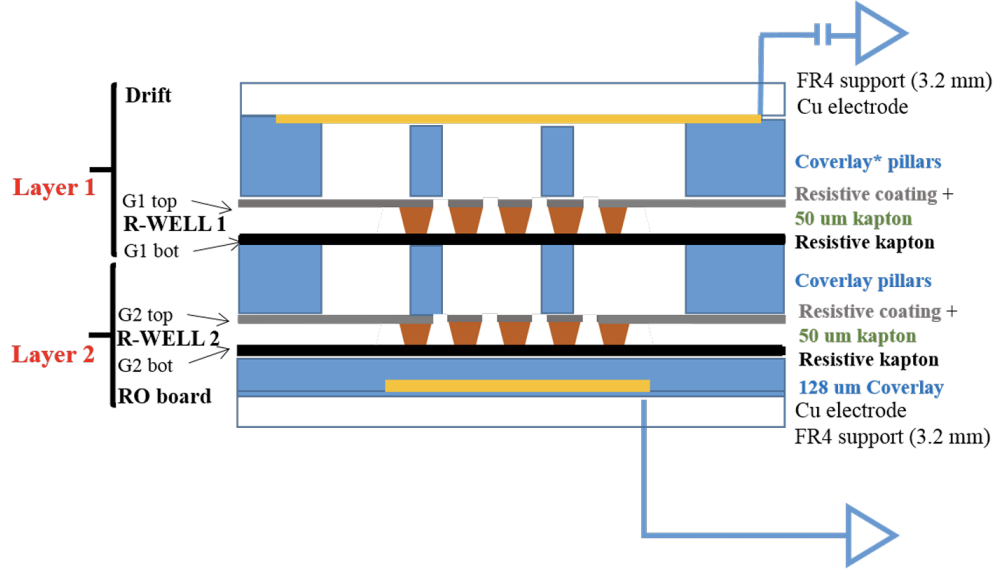


Figure 5.5: Geometry of the first FTM prototype [85].

was designed and assembled at CERN. However, all tests of characterization on the detector showed an unstable behaviour over time in sustaining high voltages, with breakdown below the electric fields for high charge amplification.

In 2018, a third FTM prototype was assembled in Bari and instrumented with small *well-like* amplification foils, similar to the ones used in the small prototype. The detector was instrumented with 4 layers each with a drift gap of $250\text{ }\mu\text{m}$; tests were performed to characterize the prototype with x-rays, but results were inconclusive due to the small current released by low-energy x-ray photons in thin drift gaps [87].

From the results obtained from these and other similar prototypes, one can conclude that the two most important factors to be controlled in the next prototypes are the amplification and stability of the single layer and the signal induction on the readout electrode from layers other than the bottom one. Two constraints can be set for the next prototype:

- the detector mechanical structure must be modular, in order to allow changing the number of layers and the thickness of each gap;
- a calibration source able to release a fixed energy in the gas, independent of the gas thickness, must be used for the characterization of the detector.

These conclusions motivate and drive the studies described in the next sections on a new FTM prototype.

5.4 Layout and structure of the FTM small-size prototype

The small-size FTM is the sixth FTM prototype designed. It was assembled and tested with the following goals:

1. test the performance of resistive amplification foils and compare it to conductive ones;
2. verify the signal induction on the readout electrode;
3. eventually prove the FTM working principle by measuring its time resolution with a variable number of layers.

The measurements described in the next sections point out that goals 1 and 2 have been realized, while achieving goal 3 still requires a few more iterations in the manufacturing of amplification foils with respect to present technology.

The mechanical layout of the detector is shown in Fig. 5.6a. The design is modular to allow changing the number of layers between one and four, while maintaining the total thickness of the active area between 5 mm and 1 cm; however, all the tests described in the next sections were performed on a single-layer detector with a drift gap of 5 mm. The electrodes all have circular shape with active region of diameter 1 cm.

The stack is enclosed in a stainless steel case (Fig. 5.6b); on the opposite sides, the case has two quartz windows of diameter 1 cm and thickness 5 mm that allow the passage of a laser beam through any drift gap for characterization tests; two mylar windows of diameter 1 cm and thickness 50 μm sit instead on the top and bottom to allow the passage of x-rays.

5.4.1 Electrode layout

The internal layout of the prototype in the case with two layers is shown in Fig. 5.7. The readout electrode is a single copper pad, of the same diameter as the other electrodes, positioned below the bottom layer; an additional copper pad is placed above the top layer for simultaneous readout.

For each layer, the *drift* electrode is the one that collects the ions from primary ionization and backflow, while the *top* electrode (or *cathode*), is the one collecting the avalanche ions; the *bottom* or *anode* is the electrode that collects the electrons from the avalanche. Drift and anode are both made of a 25 μm -thick layer of Kapton XC of surface resistivity 50 $\text{M}\Omega/\square$ glued on top of a disk of polyimide; at the interface between two layers (e.g. the drift on the bottom layer and the anode of the top layer) the electrodes are glued together back-to-back on a single polyimide disk (Fig. 5.8). The amplification foil is made of a polyimide layer of thickness 50 μm coated on top by a 100 nm-thick layer of DLC (the cathode); the amplification holes have the shape of a truncated cone with pitch 140 μm and design diameters 70 μm on the bottom and 50 μm on the top. The hole geometry is similar to the amplification foil of a $\mu\text{-RWELL}$, as shown in Fig. 5.9, with three essential differences:

- the top electrode in the FTM is made of DLC instead of copper;
- the hole geometry is inverted (the largest hole diameter being on the bottom on the FTM) due to the different manufacturing process, as explained in the next section;

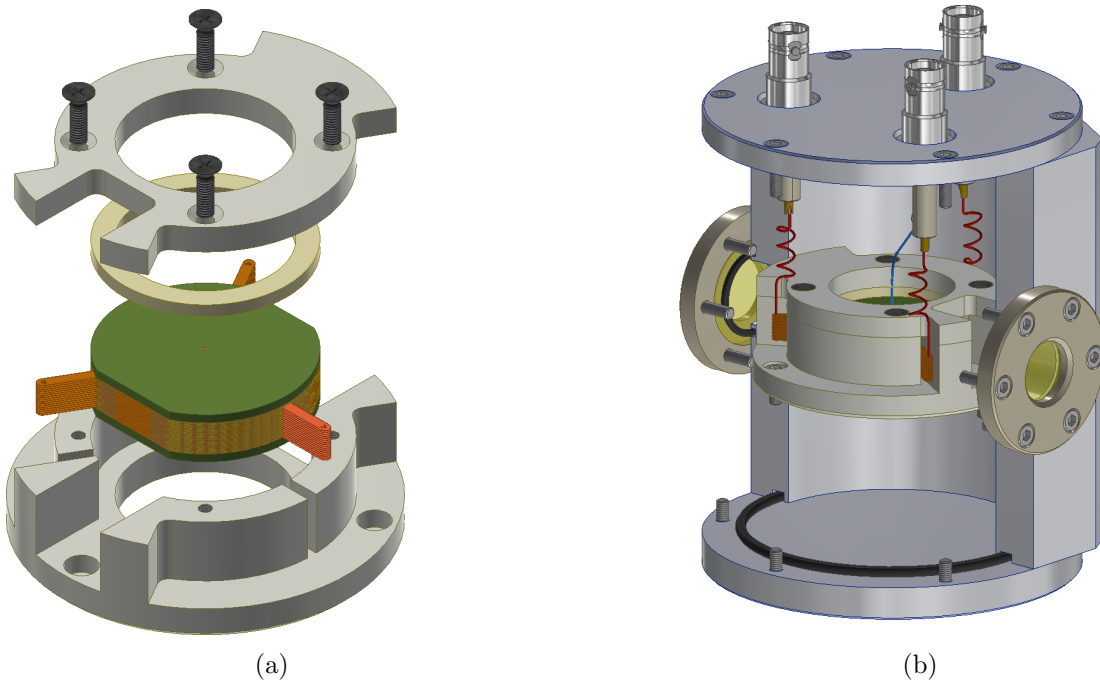


Figure 5.6: (a) Exploded view of the small FTM layout. The layers are stacked with the drift gaps defined by spacers. (b) Section of the FTM showing the inner stack sitting in the steel case. The quartz windows are shown at the two sides.

- the amplification foil is not glued to the bottom electrode, as available technologies do not presently allow etching a laminate coated by resistive materials on both sides – this is an active area of R&D.

The drift gap thickness is defined by spacers at the edge of the electrodes; as the amplification foils and the anode are separate foils, the attachment between the two is guaranteed only by electrostatic force when voltage is applied. In the original prototype design, the two readout electrodes are not glued to the rest of the layout, but held fixed mechanically.

5.4.2 Amplification foil production for the FTM

The etching of resistive foils for the FTM follows a different procedure from the established one for traditional GEM foils due to the constraining presence of resistive materials only.

The starting material for the etching is a flexible copper clad laminate (FCCL) made of a 50 μm -thick polyimide layer covered by a 100 nm-thick DLC layer on top and two 7 μm copper layers on both sides; the adhesion between DLC and copper is improved by the addition of a 10-nm chromium layer between them. The resistive coating is performed by magnetron sputtering [88], a technique that allows the deposition of atoms obtained from a carbon target driven by a magnetic field towards a substrate; such procedure has been proven to allow fast deposition over large samples to obtain DLC layers with high surface resistivity. The resistivity

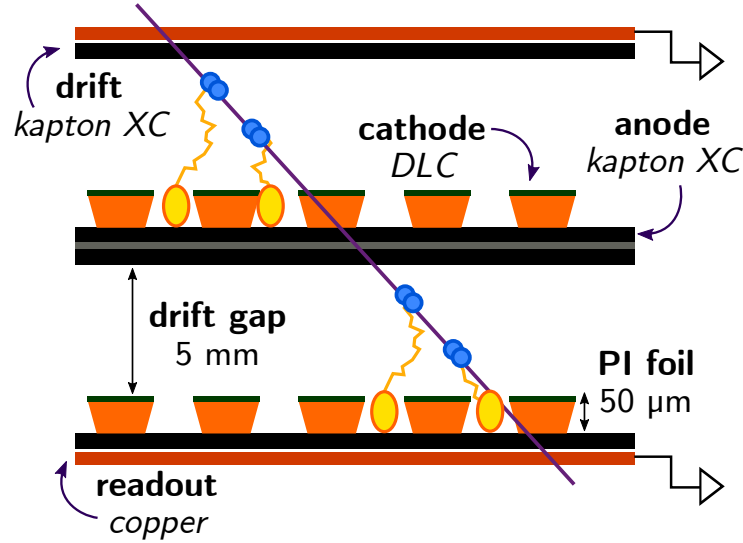


Figure 5.7: Layout of the FTM instrumented with two layers.

of the foils tested in the FTM is $100 \text{ M}\Omega/\square$.

All the FTM foils tested in the measurements described below are obtained by magnetron sputtering performed in USTC. Despite its reliability, this coating process in the past has shown issues of uniformity in the DLC attachment to the polyimide, with risk of DLC damage when high voltage was applied to the foils. An alternative deposition technique, pulsed laser deposition (PLD), has lately shown promising results on small samples, with the possibility of tuning the DLC resistivity over a wide range by changing the laser pulse energy [89]; at the moment of writing, FTM foils obtained from PLD at INFN Lecce are being tested and this technology is being considered for the production of small “home-made” FTM foils with R&D purposes, but more work is needed to scale it to larger surfaces.

Once the starting FCCL is ready, the amplification foil is obtained by etching; for the FTM foils the procedure has been carried at the CERN MPT workshop. The steps of the foil etching are the following, shown in Fig. 5.10:

1. The etching starts from the bottom, with the copper layer covered by a photoresistive layer and then patterned by photolithography.
2. The laminate is placed in a chemical bath, where the polyimide is etched in a solution of ethylenediamine ($\text{C}_2\text{H}_8\text{N}_2$) and potassium hydroxide (KOH).
3. The top protective chromium and copper layers are removed, leaving the DLC uncovered.
4. The remaining DLC in correspondence to the holes is mechanically removed.

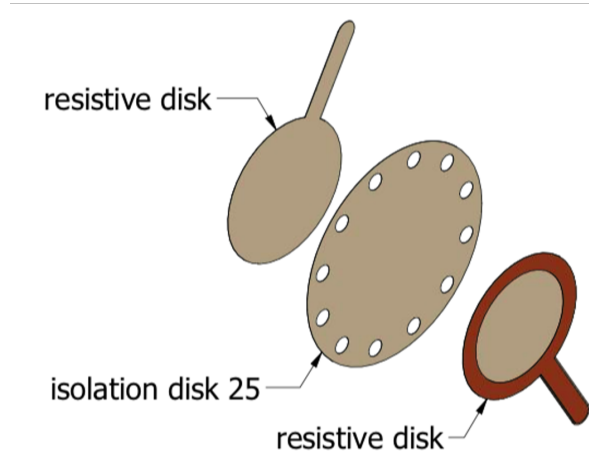


Figure 5.8: Layout of two resistive electrodes (drift and anode) of two separated layers glued back to back.

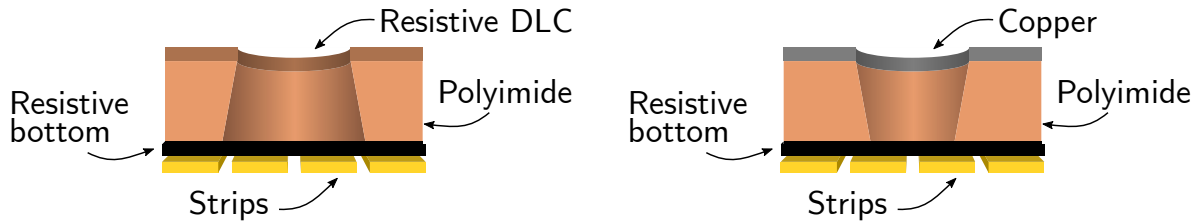


Figure 5.9: On the left, layout of an FTM amplification foil. On the right, layout of the amplification foil of a μ RWELL.

5.5 Laser setup for the characterization of the FTM

X-ray sources are widely used for the characterization of gaseous detectors; however, as mentioned above, they are not the optimal solution for the FTM because of two main reasons:

- low-energy x-rays (less than 10 keV) have low penetrating power in a multi-layer structure made of PCB material, while higher-energy x-rays have low cross-sections in typical gas mixtures. In other detectors, the x-ray spectrum is converted to a monochromatic copper fluorescence spectrum (peaked at 8.9 keV) by interaction with a copper cathode, but the FTM only has resistive electrodes;
- in thin drift gaps, part of the energy released by photons in the keV energy region is lost without being converted to primary electrons in the gas, so the total number of primaries created by ionization by a single X-ray photon is subjected to large fluctuations (Fig. 5.11).

Beside allowing to test one layer of the detector at a time, laser beams can release a fixed energy in detectors of small gas volumes; a laser test bench then allows the characterization

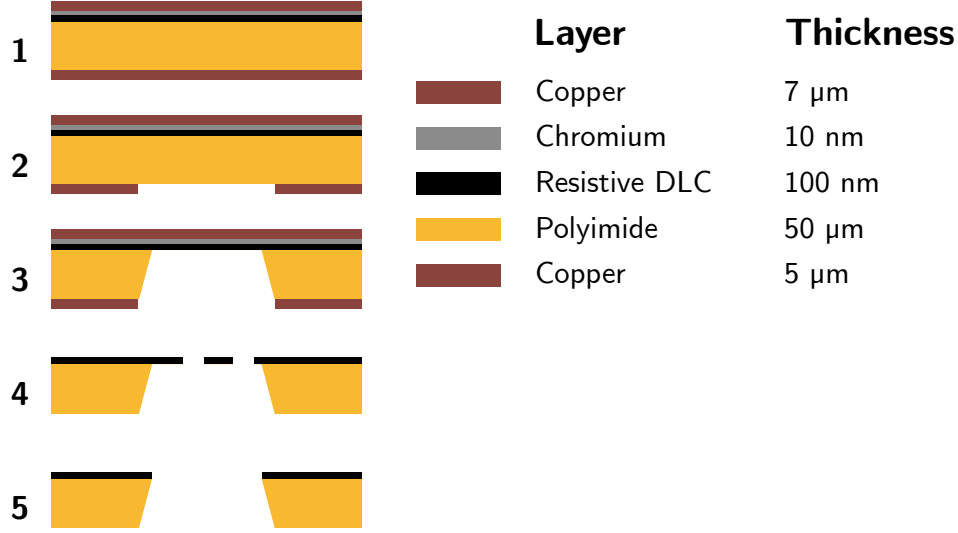


Figure 5.10: Etching steps of FTM amplification foils.

of detectors with drift gaps thinner than 500 μm. A test setup using a UV laser has been assembled for the characterization of the FTM.

5.5.1 Laser beam interaction with gas

Laser rays are known to produce ionization in common gas mixtures used to fill detector volumes by interaction with small-concentration impurity molecules, which are naturally present due to outgassing of the detector walls or the gas pipes [90]. Such molecules have low ionization potential (9 eV or less) and can be ionized in multi-photon processes by ultraviolet laser beams.

The rate of ionizations per unit volume due to n -photon absorption for an impurity species of molecule density N (in m^{-3}) is

$$\frac{R}{V} = N\sigma^{(n)}\phi^n, \quad (5.4)$$

where ϕ is the flux of the laser beam (i.e. the number of photons crossing a unit area per unit time, measured in $\text{cm}^{-2}\text{s}^{-1}$) and $\sigma^{(n)}$ is the n -photon cross-section equivalent, measured in $\text{cm}^{2n}\text{s}^{n-1}$.

At low beam intensities, two-photon ionization dominates, with a ionization rate density

$$\frac{R}{V} = \left(\frac{\lambda}{hc}\right)^2 N\sigma^{(2)}I^2, \quad (5.5)$$

where $I = (hc/\lambda)\phi$ is the laser beam intensity and A is the laser spot size at the ionization point. This equality can be obtained by solving the semi-classical rate equations for the population density of the impurity species.

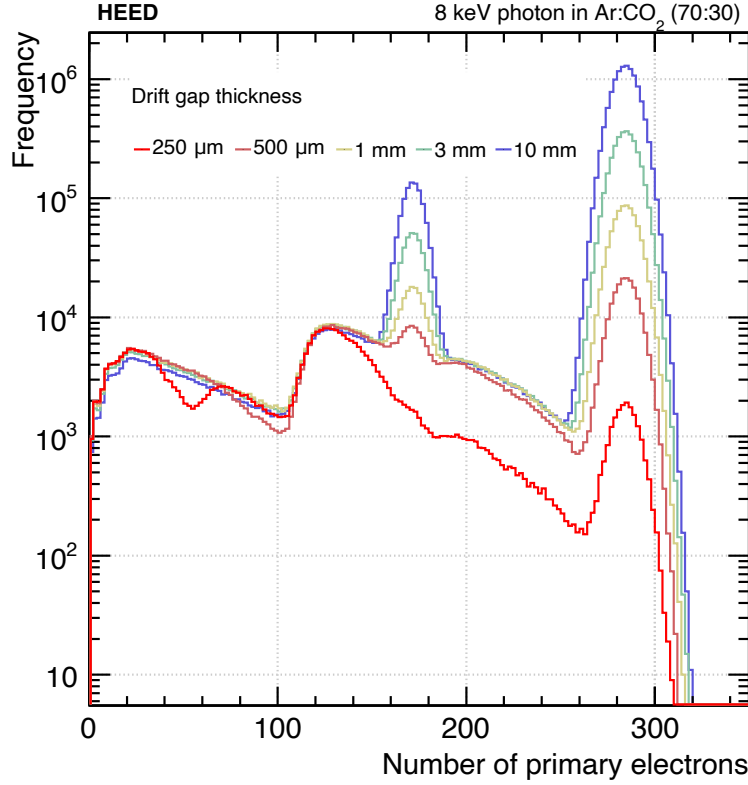


Figure 5.11: Simulated spectrum of the energy deposit in a drift gap of decreasing thickness by a primary photon of 8 keV. For a drift gap of 500 μm or less the spectrum fluctuations prevent resolving the primary ionization energy.

5.5.2 Laser setup specifications

The optical setup is made of a Nd:YAG pulsed laser of 266 nm wavelength (CryLaS 266-50), short enough to ionize typical impurity molecules like benzene, toluene and cumene by two-photon interaction (Tab. 5.1). The energy of a single laser pulse (controllable through an external attenuator) is 51 μJ and the pulse duration is of 0.9-1.3 ns FWHM, about one order of magnitude shorter than the de-excitation times of many hydrocarbon molecules. The waist radius is $400 \pm 100 \mu\text{m}$, so that the beam intensity at the laser head is $101 \pm 51 \mu\text{J}/\text{mm}^2$ – known to be sufficient for a ionization yield equivalent to several minimum-ionizing particles.

Table 5.1: Specifications of the CryLaS FQSS266-50 laser.

Pulse energy	Waist radius	Wavelength	Pulse duration	Spatial mode
51 μJ	400 μm	266 nm/4.7 eV	1 ns FWHM	TEM_{00}
can provide a MIP-like energy deposit	low angular divergence	two-photon ionization of hydrocarbons	lower than single-layer time resolution	gaussian beam quality < 1.5

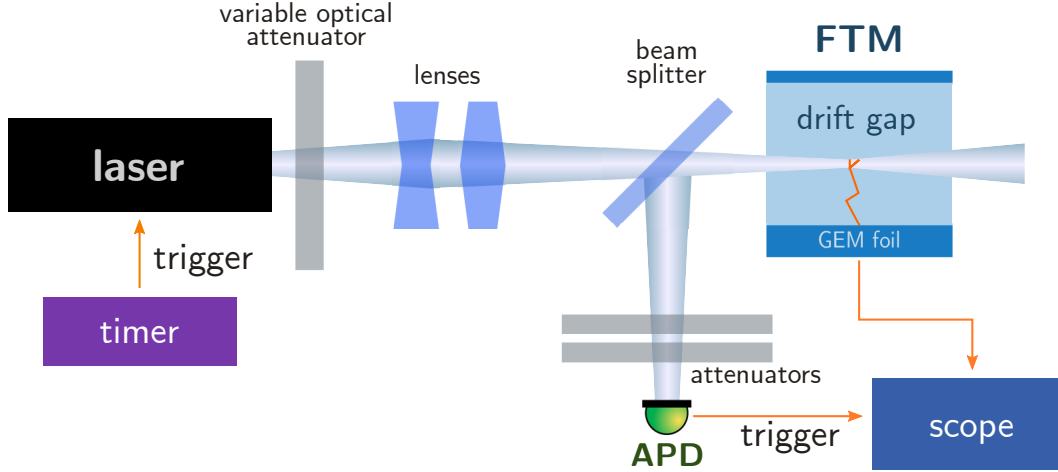


Figure 5.12: Sketch of the laser setup. The laser is triggered by a dual timer and the beam is attenuated by a first set of variable filters and focused; half of the beam is further attenuated and sent to an avalanche photodiode for triggering with time precision of the order of tens of picoseconds.

The full laser setup is depicted in Fig. 5.12. The laser beam is attenuated by a set of variable optical filters to adjust its intensity and focused by three lenses (of focal lengths 75, 750 and 200 mm respectively) down to a waist radius of $23.4\text{ }\mu\text{m}$, in order to obtain a narrow point of primary ionization in the detector gas. At full pulse energy, the beam intensity in the waist in this configuration is $3 \times 10^4\text{ }\mu\text{J}/\text{mm}^2$. The beam is divided by a 50%-50% beam splitter and is sent both to the detector (where it enters the drift gap through the quartz window) and to an avalanche photodiode (Thorlabs APD430A) used as a trigger. The time resolution of the trigger APD was measured by irradiating in coincidence two identical APDs³ and found lower than 50 ps.

5.6 Characterization of the small-size FTM

5.6.1 Signal transparency

A preliminary observation of transparency to the readout signal has been performed by reading out the signal simultaneously at the top and bottom readout electrodes. Fig. 5.13 shows the readout signal at the top and bottom electrodes for a laser pulse energy of $1.9\text{ }\mu\text{J}$. The readout is triggered by the APD at the beginning of the laser pulse and the signals from the two readout pads are acquired on the oscilloscope after being amplified by a linear preamplifier (Cividec C2-HV). The two readout pads observe a similar charge, suggesting that the layer is electrically transparent.

³The time resolution of each APD was then calculated from the jitter $\sigma_{1,2}$ of the signals from the two APDs as $\sigma_{12}/\sqrt{2}$.

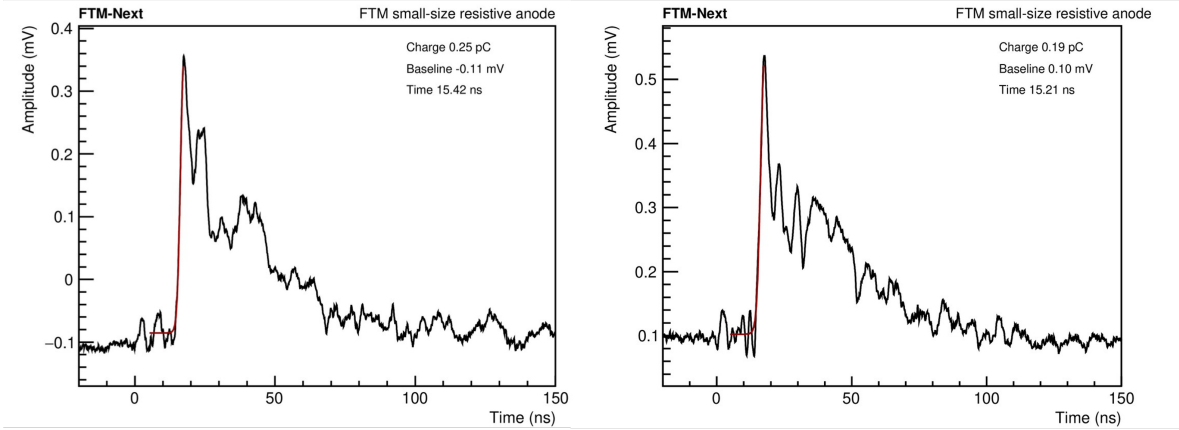


Figure 5.13: Example of signal induced by laser ionization read out by the top and bottom electrodes for a laser pulse energy of $1.9 \mu\text{J}$; the top signal is inverted. The readout preamplifier is a Cividex C2-HV and the charge is calculated as the integral of the current signal divided by the preamplifier gain of 100; the red line is a fit of the rising edge with a sigmoid function.

5.6.2 Current measurement

Fig. 5.14 shows an example of the currents measured on the three electrodes as a function of the amplification voltage, i.e. the voltage difference between cathode and anode. The drift field is set at 3 kV/cm and the laser output power is set to $4 \mu\text{J}$; the current measurement is performed with an ammeter of 100 fA resolution (Keysight 2980).

We distinguish two regimes of operation:

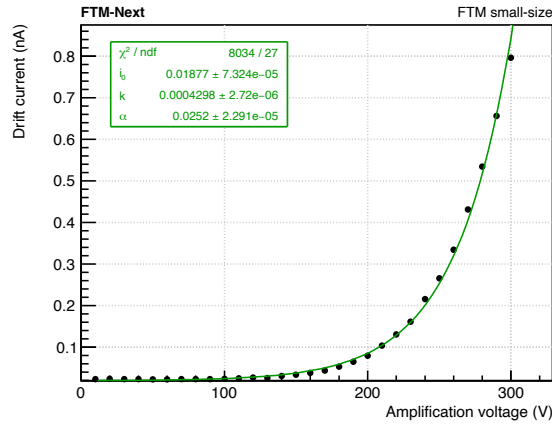
- at low amplification voltage, the multiplication is equal to 1 (*ionization regime*) and most of the primary ionization electrons are collected at the cathode, while the anode collects the (few) electrons which enter the holes. Both cathode and anode currents are negative, but $|i_{\text{cathode}}| > |i_{\text{anode}}|$; the drift electrode collects the primary ionization ions;
- at higher amplification voltage, the avalanche electrons are collected by the anode, on which the induced current is negative, while on the cathode the current is positive and mostly induced by the avalanche ions; the drift current is positive and due to the primary ionization ions and the backflow ions.

In both cases, the total current is zero as expected by charge conservation.

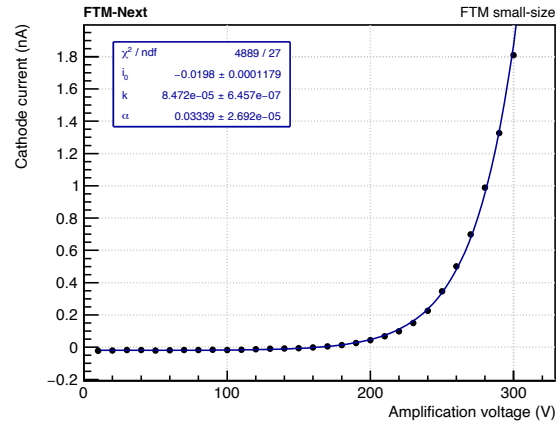
5.6.3 Gain measurement

The effective gain of the prototype has been measured in the laser setup instrumented with different amplification foils. The detector effective gain is defined as the ratio between the number of electrons collected at the anode and the number of primary ionization electrons and can be measured as $g_{\text{eff}} = i_{\text{anode}}/i_{\text{primary}}$.

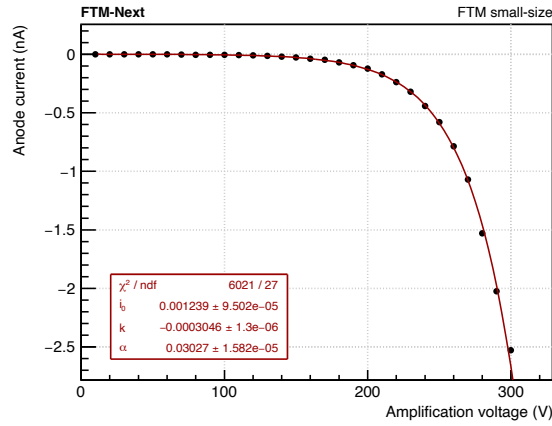
While the anode current (of the order of a few nA) can be measured directly with the femtoammeter, the primary current is measured in the ionization regime, in which the primary



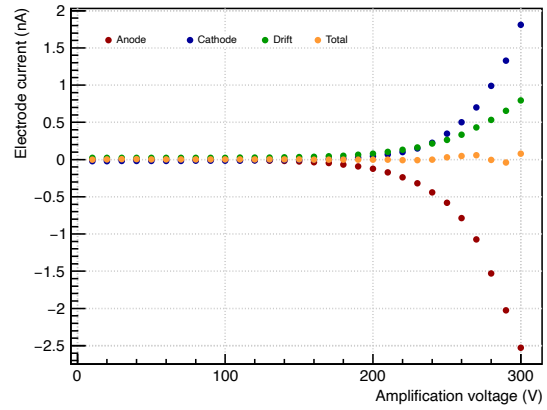
(a)



(b)



(c)



(d)

Figure 5.14: (a), (b), (c) Currents on the three electrodes as a function of the amplification voltage fitted with exponential function of the form $i_0 + ke^{\alpha V}$. (d) Currents on the three electrodes overlapped with the total current; the deviation from zero of the sum is due to leakage currents.

ionization electrons are collected either from the cathode or from the anode; therefore, for the gain calculation the primary current is measured as the sum of the cathode and anode currents. The value of the primary current in the primary ionization regime is obtained by fitting the trend of current as a function of the amplification voltage (see Fig. 5.14) with an exponential function of the form $i_0 + ke^{\alpha V}$ for each electrode, scanning a voltage range between 10 and 250 V; the primary current is the sum of the i_0 and k parameters extracted from the fit.

At first, the gain measurement was performed in Ar:CO₂ 70%:30% and then repeated after replacing the resistive foil with another amplification foil with copper as top electrode (for the difference between the two structures refer again to Fig. 5.9). Fig. 5.15 shows the effective gain as a function of the amplification voltage. The drift field is fixed at 3.5 kV/cm, as it maximizes the transfer efficiency, as shown from the drift scan in Fig. 5.16. At a fixed applied voltage, the resistive foil shows an effective gain equal to twice the gain of the conductive foil; a simulation study comparing the *normal* and *inverted* well geometries shows that this difference is exclusively to be ascribed to the difference in the hole shapes. However, the overall highest gain reachable with the conductive layout is higher than the gain in the resistive layout, because of the higher amplification voltage reachable before the onset of discharge; moreover, the maximum gain reachable with the resistive foil, of 1000, is lower than the minimum gain needed for a detector efficient to MIPs.

The low gain in Ar:CO₂ suggests other gas mixtures must be compared to determine the one for best amplification: besides argon, also neon was tested as active gas, while CO₂, CF₄ and iC₄H₈ were used as quenchers. Fig. 5.17, shows the gain trend of the resistive foil in different gas mixtures: while CF₄-based mixtures – considered for their high drift velocity – did not allow large amplification due to discharges observed even at low amplification fields, mixtures with isobutane showed more promising results, particularly with Ne:iC₄H₈ 90%:10% that allowed reaching gains up to 3×10^4 . Such gain would allow operating the detector with thin drift gaps to detect single primary electrons with readout electronics – such as the VFAT3 – featuring an equivalent noise charge of the order of 1000 electrons; however, even a gain of the order of 10^4 is not satisfactory for timing applications, since fast readout electronics sensitive to a signal rising edge have a typically worse signal to noise ratio.

An explanation for the lower stability to high fields for the resistive foils with respect to the conductive ones has been obtained by observing the hole pattern on the microscope (Fig. 5.18). The two pictures on the left show the top and bottom sides (respectively made of copper and polyimide) of the conductive foils, with circular hole shapes of high regularity; by comparison, the resistive foil (in the two pictures on the right) shows an highly irregular hole shape not only on the top (DLC) side, but also on the bottom (polyimide) side. The resulting local irregularities in the electric field are associated with the increased discharge probability.

The origin of such DLC delamination can be pointed to one of the central steps of the foil production from the original laminate (Fig. 5.19). During the polyimide etching, the etching solution enters in contact with the DLC, possibly infiltrating in the DLC itself due to imperfect adhesion in the polyimide-DLC interface; this causes an over-etching of the polyimide holes resulting in the observed irregular polyimide and DLC borders.

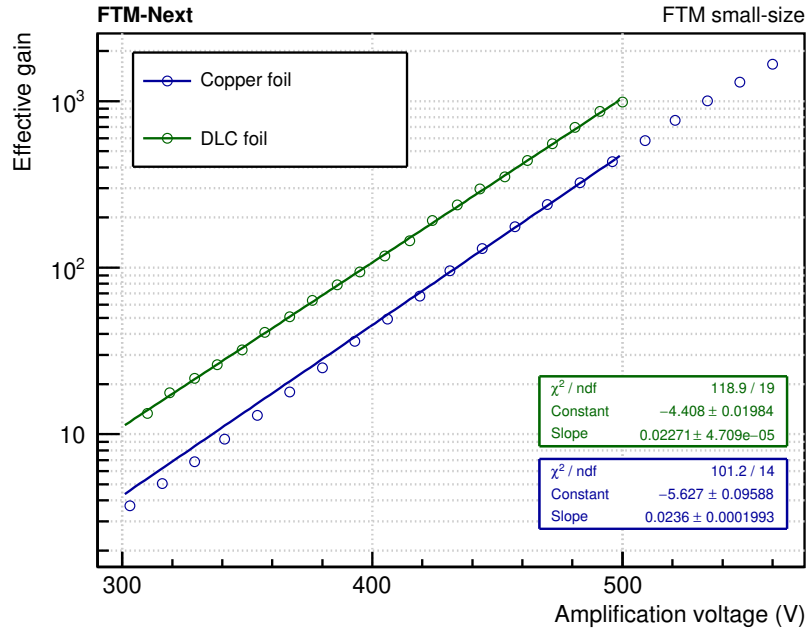


Figure 5.15: Effective gain in Ar:CO₂ 70%:30% of the single-layer FTM instrumented with amplification foils with copper top (blue) or DLC top (green).

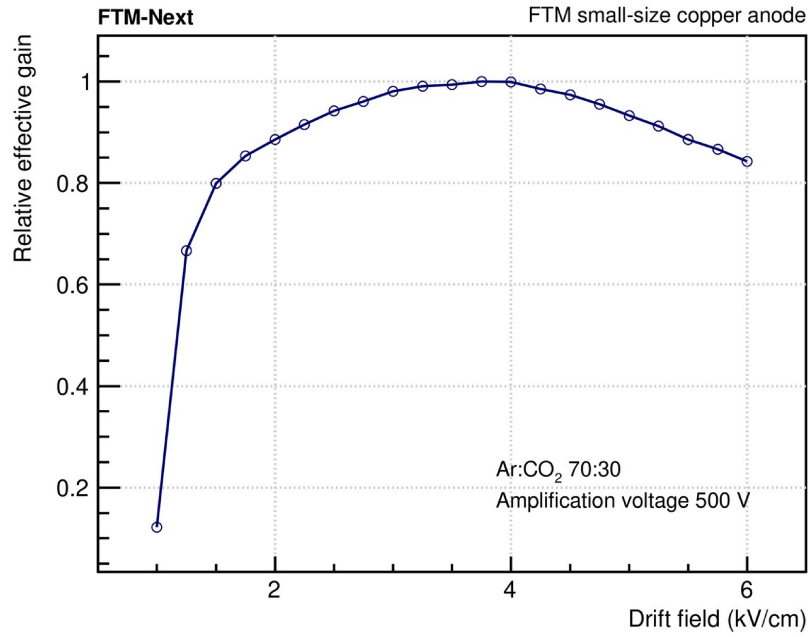


Figure 5.16: Gain of the FTM as a function of the drift field normalized to its maximum value. The gain is shown to saturate at 4 kV/cm.

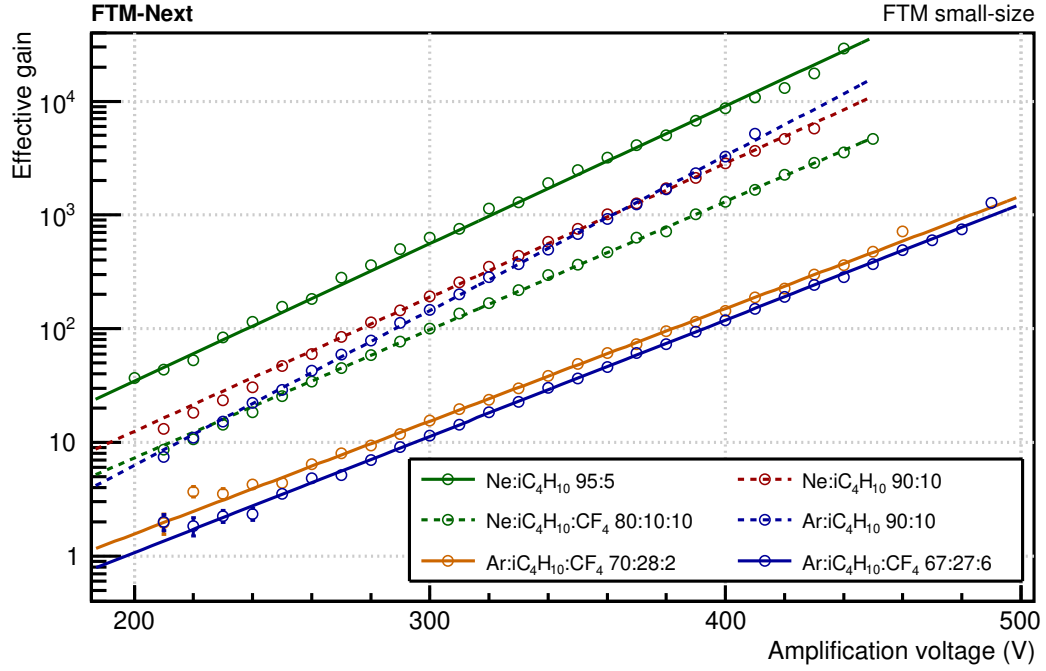


Figure 5.17: Effective gain of the FTM measured with different gas mixtures.

5.6.4 Efficiency

The efficiency of the FTM is measured in a laser pulse energy scan. The laser pulse energy is varied between 1 and 51 μJ ; for a fixed pulse energy, the following steps are followed:

- to determine the primary charge per pulse, the primary ionization current is measured from the ratio between the anode current – measured with a femtoammeter – and the effective gain; the corresponding average charge per event is obtained from the ratio $q_{\text{primary}} = i_{\text{primary}}/f_{\text{pulse}}$, where the laser pulse rate f_{pulse} is kept fixed at 100 Hz.
- The FTM readout is acquired through a Cividex C2-HV linear preamplifier by sampling each signal with an oscilloscope triggered by the avalanche photodiode; the efficiency is measured as the ratio between the number of recorded signals over threshold and the total number of pulses sent by the laser.

Fig. 5.20 shows the calibration curve for the primary current as a function of the laser pulse energy fitted with a power law. The exponent of the fit is 1.4, in agreement with the fact that the trend of the laser ionization is expected to be quadratic at low energies and linear at higher energies. Fig. 5.21 shows the result of the efficiency scan: the primary charge required for an efficiency higher than 90% is 4500 primary electrons, much higher than the value required for a good efficiency to MIPs in a traditional MPGD (a few tens of electrons) and even less than the primary charge for an FTM with a drift gap of 250 μm per layer. Moreover, the measurement is in disagreement with the expected efficiency obtained from the

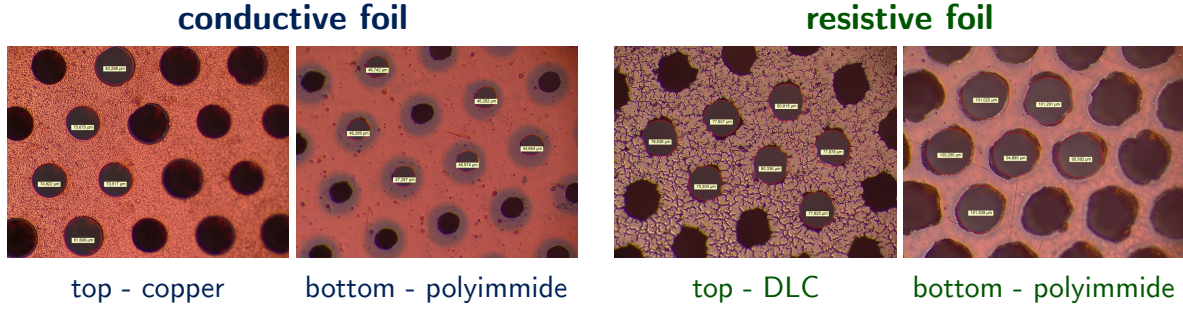


Figure 5.18: Pictures of the FTM amplification foils with DLC (left) and copper (right) anode taken at the microscope.

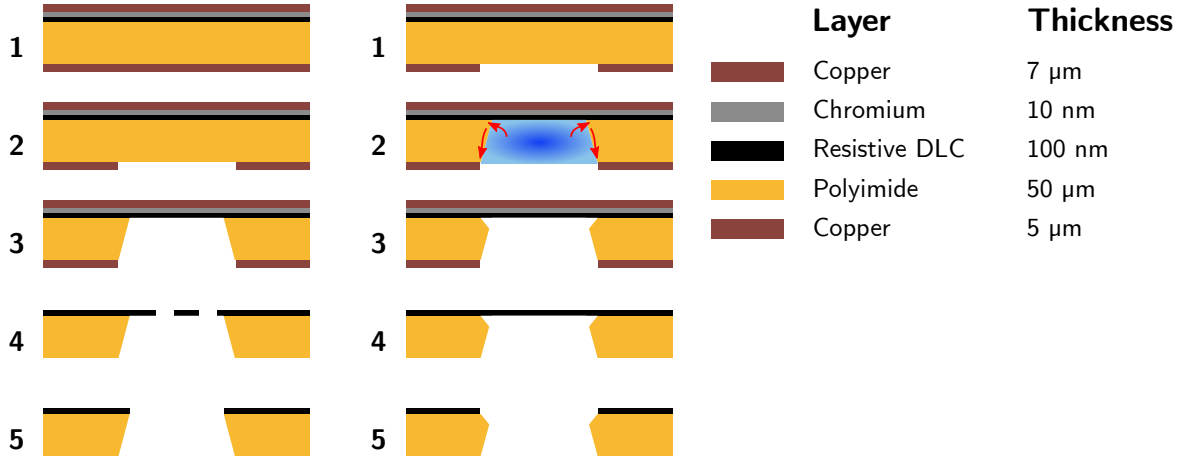


Figure 5.19: On the left, etching steps of FTM amplification foils; on the right, over-etching of the polyimide leading to the delamination of the DLC.

effective gain, 1.6×10^4 , for which the detector is expected to be efficient to a few hundreds of primary electrons when read out by a linear amplifier⁴.

The different results between the charge multiplication measured from the current and the efficiency measured from the signal can be explained as a signal induction issue, specifically in the capacitive coupling of the detector with the readout pad. The readout electrode is made of a copper layer of 25 μm thickness glued on a 50 μm support disk; the adhesion between the copper disk and the electrode immediately above it (i.e. the anode of the bottom layer) is guaranteed only by the weight of the stack and is not sufficient to ensure perfect attachment. A thin gap between the two electrodes is clearly visible; due to the dependence of the weighting field of the readout pad from the distance between the two electrode, even a gap of a few

⁴For a detector operated at a gain of 1.6×10^4 , a primary charge equivalent to 200 primary electrons corresponds to an amplified charge of 511 fC. With a linear preamplifier with amplification 100, assuming an electron peak lasting 10 ns, such charge would yield a readout signal of the order of 10 mV, which is visible on an oscilloscope.

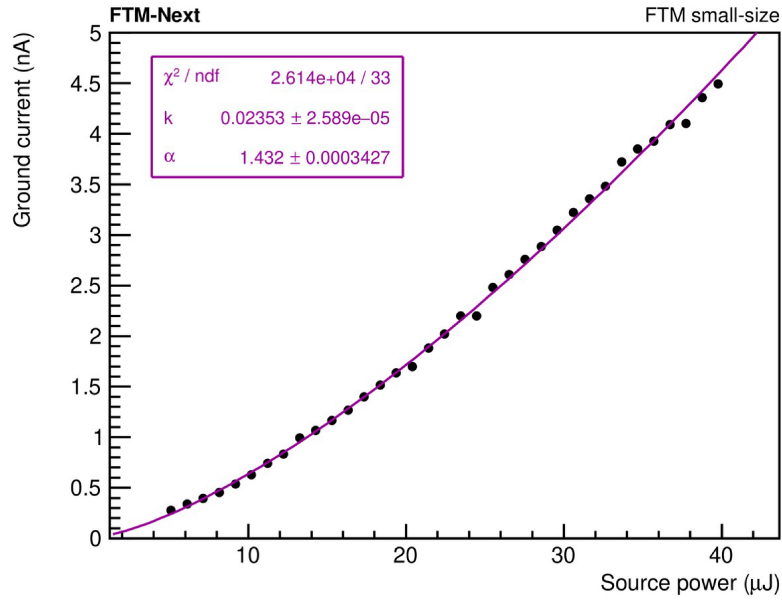


Figure 5.20: Anode current of the FTM as a function of the laser pulse energy fitted with a power law.

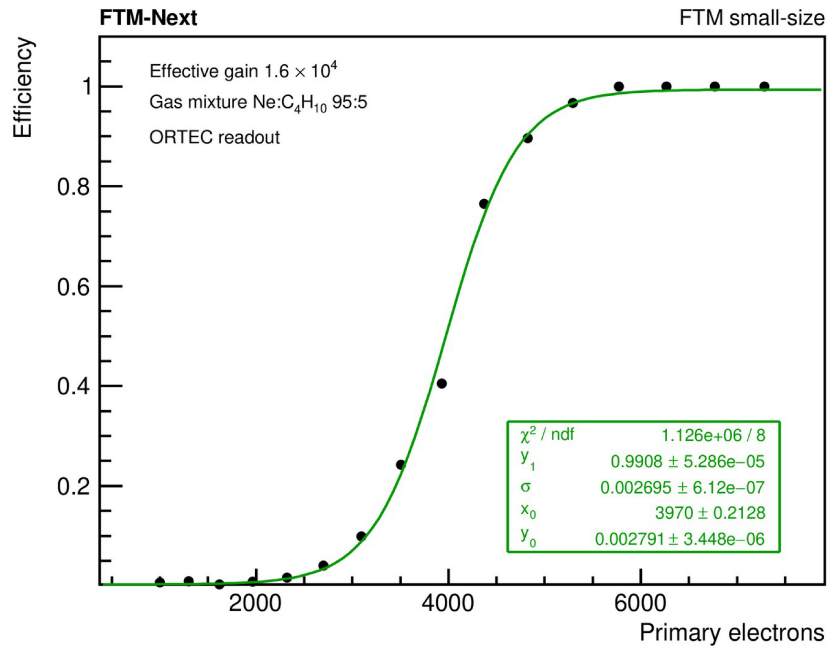


Figure 5.21: Efficiency of the FTM as a function of the primary charge in the original layout.

hundreds of μm can strongly attenuate the signal. This issue was found out to have been overlooked in all FTM prototypes – which all had no adhesion between the bottom layer and the readout plane, with the exception of the first prototype, that was also the only one not showing signal induction issues.

The adhesion of the readout pad to the anode was solved by slightly modifying the detector layout, replacing the two anode and the readout disks with a single one, as shown in Fig. 5.22. The new unified electrode is made of a kapton XC anode glued through a $25\text{ }\mu\text{m}$ -thick pre-preg layer to the readout copper pad; the copper layer is in turn glued to a kapton support disk, on whose other face a copper plating allows soldering the readout connector.

Fig. 5.23 shows the efficiency of the detector with the new readout foil: the detector in this case reaches full efficiency at 200 primary electrons. The main limit in the efficiency is in this case the maximum gain reachable with resistive foils.

5.7 Development of a time-tagger for the FTM

In view of future FTM development, a precise measurement of the detector time resolution would require a good time reference.

Three different detectors for time-tagging have been tested: a multi-anode photomultiplier, a micro-channel plate photomultiplier and a scintillator coupled with silicon photomultipliers.

5.7.1 Multi-anode PMT

The time resolution of traditional photomultipliers is dominated by two factors:

- the transit-time spread (TTS) of the photoelectrons between the photocathode and the first dynode;
- the TTS between the first dynodes, i.e. in the beginning of the avalanche.

Traditional photomultipliers can reach a sub-nanosecond time resolution for single electrons; multi-anode PMTs (MaPMTs) have dynodes divided in discrete elements in the plane perpendicular to the avalanche development, which gives two-dimensional position information.

The tested MaPMTs are two Hamamatsu H8500C [91] (Fig. 5.24a), a 12-dynode PMT with bialkali photocathode and anode segmented in 8×8 pads of $5 \times 6\text{ mm}^2$ each. The photocathode is covered by a 1.5-mm borosilicate glass window that acts as a Cherenkov radiator at the passage of a charged particle.

The two MaPMTs were tested both with cosmic rays and with muons in a test beam at the CERN North Area with a similar setup (Fig. 5.25): the devices are aligned on a rail and enclosed in a dark box. The detectors are operated at a nominal gain of 2×10^6 with a bias voltage distributed through a voltage divider. The output signals are read out in coincidence by a common pin connected to the last dynode and the wave forms are saved on an oscilloscope and analyzed offline.

Fig. 5.26a shows the output signal of both MaPMTs in a single event. To determine the time resolution the MA-PMTs, the signals were fitted with a sigmoid function to extract their arrival time; Fig. 5.26b shows the distribution of the event-by-event arrival time difference

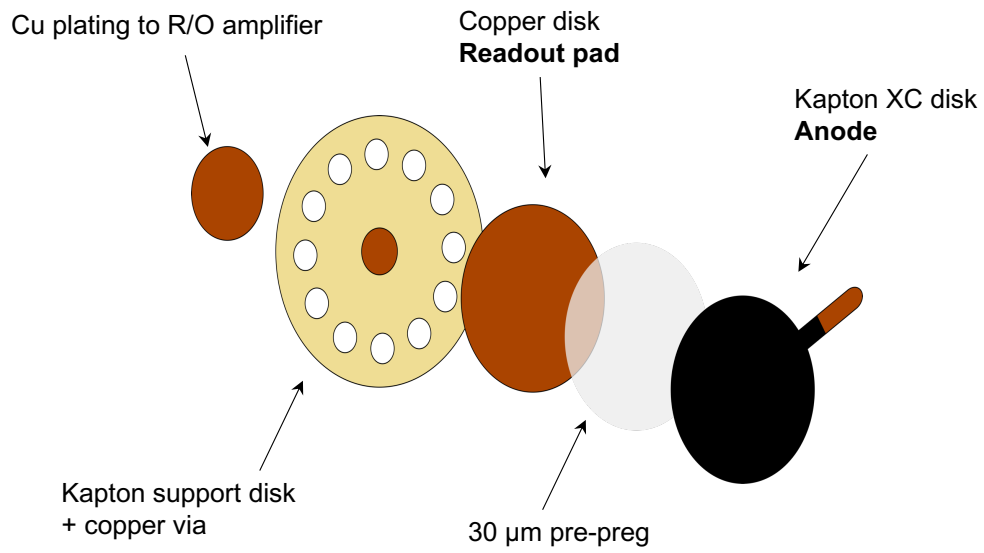


Figure 5.22: Layout of the new readout disks for the improvement of the signal induction.

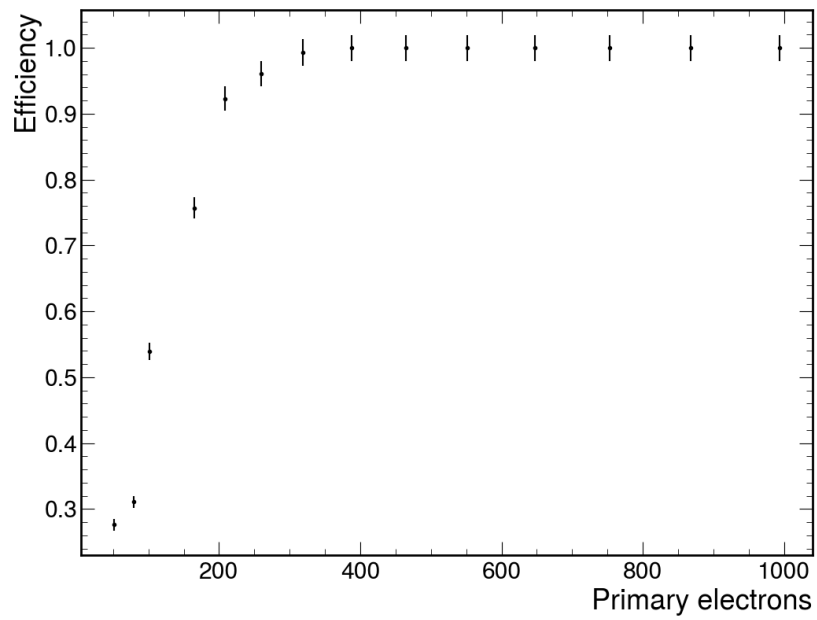


Figure 5.23: Efficiency of the FTM as a function of the primary charge in the modified layout.

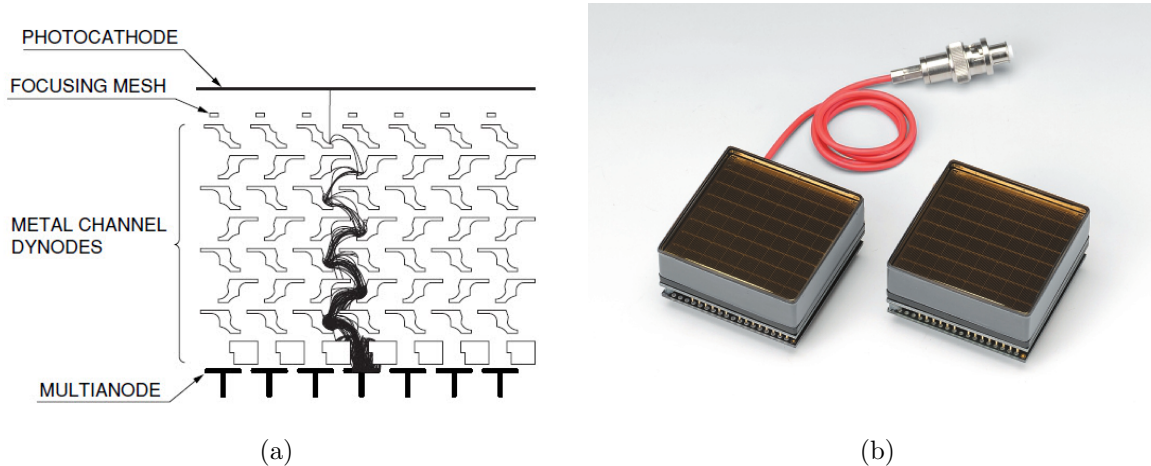


Figure 5.24: (a) Schematic layout of an MaPMT, from [92]. (b) Picture of the two MaPMTs tested [91].

between the two PMTs. The time resolution of each MA-PMT is estimated as $\sigma_2/\sqrt{2} = 81$ ps, where σ_2^2 is the variance of the signal time difference distribution as obtained by a gaussian fit. No significant variation is observed between the time resolution measured with cosmics and in test beam.

5.7.2 Micro-channel plate PMT

The layout of a micro-channel plate photomultiplier (MCP-PMT) is similar to the one of a traditional PMT, but the discrete dynodes are replaced by a glass capillary plate (Fig. 5.27 left). A voltage difference is applied between the top and bottom electrodes of the micro-channel plates and the electron multiplication happens between the walls of the channels (Fig. 5.27 right), with a total gain that depends on the ratio between the capillary length and its diameter; the transit-time spread between two multiplication collision can be made smaller and smaller by reducing the channel diameter, so that the main contribution to the MCP-PMT time resolution is the transit-time spread of the photoelectrons and can be as low as 27 ps for a single photoelectron [93].

The tested device is a Planacon XP85012 [95]; its amplification region is made of two cascaded chevron micro-channel plates (Fig. 5.28) of channel diameter 25 μm . The bi-alkali photocathode is coupled to a 1.3-mm thick sapphire window used as a quartz radiator; the detector active surface is $53 \times 53 \text{ mm}^2$ and the anode plane is divided in 8×8 readout pads. The bias is distributed through a voltage divider.

Literature studies on the device report a single-photoelectron time resolution of 37 ps [96]; I could not reproduce the same result due to the lack of a precise time reference. However, the UV laser used for the characterization of the FTM could still be used for a measurement of the MCP-PMT single-photoelectron charge spectrum and its gain.

The measurement setup is shown in Fig. 5.29: the laser beam was splitted through a 50%:50% beam splitter and reached both the reference APD and, after a set of attenuators,

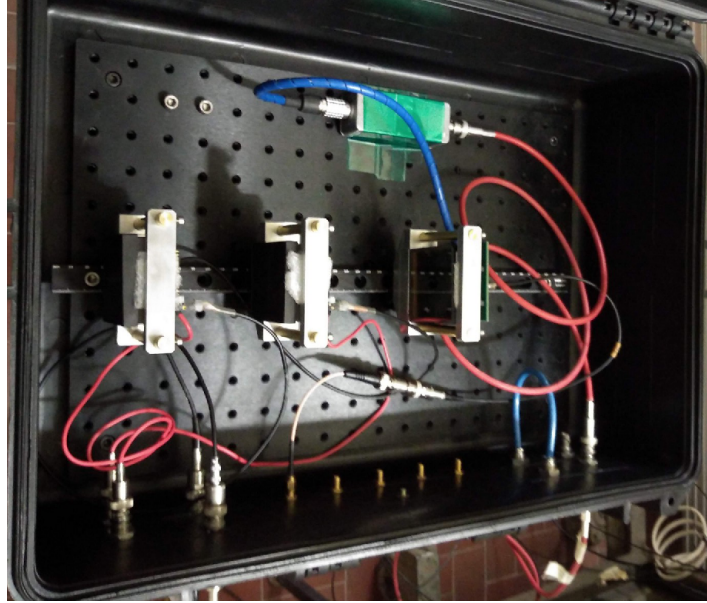


Figure 5.25: Setup for the time resolution measurement of the two MaPMTs (left and center), showing also a MCP-PMT on the right.

the MCP-PMT. The MCP-PMT signals were acquired and saved on an oscilloscope through a custom board that allowed common read-out of the four central anode pads; the readout was triggered by the reference APD. Starting from an arbitrary laser power, the signal charge was calculated from the integral of the signal waveform and its charge spectrum was monitored. to reach the single photo-electron regime, the laser power was lowered until the shape of the charge spectrum stopped changing for small power variation; this condition indicated that the majority of the laser pulses generated either zero or one photoelectron in the MCP-PMT, the probability of 2 photoelectrons being negligibly small.

Fig. 5.30a shows the single-electron charge spectrum of the MCP-PMT for a fixed bias point of 2350 V after the pedestal has been fitted with a gaussian and subtracted; the spectrum is fitted with a Polya distribution and the average charge is extracted from the fit; the effective gain is the ratio between the average charge and the electron charge. Fig. 5.30b shows the trend of the gain as a function of the bias point, which demonstrates that the detector can reach an effective gain of the order of 10^7 .

Fig. 5.31 shows the distribution of the signal arrival times (SATs) of the device (with respect to the reference APDs). Due to the large time duration of the laser pulse (quoted at 1 ns FWHM), this measurement is not sensitive to the time resolution of the MCP-PMT, but instead shows that the time structure of the laser pulse is divided in two bunches.

5.7.3 Silicon photomultiplier readout of scintillators

Silicon photomultipliers (SiPMs) are an attractive and cost-effective timing solutions for their excellent time and energy resolutions, being able to resolve charges of single photoelectrons

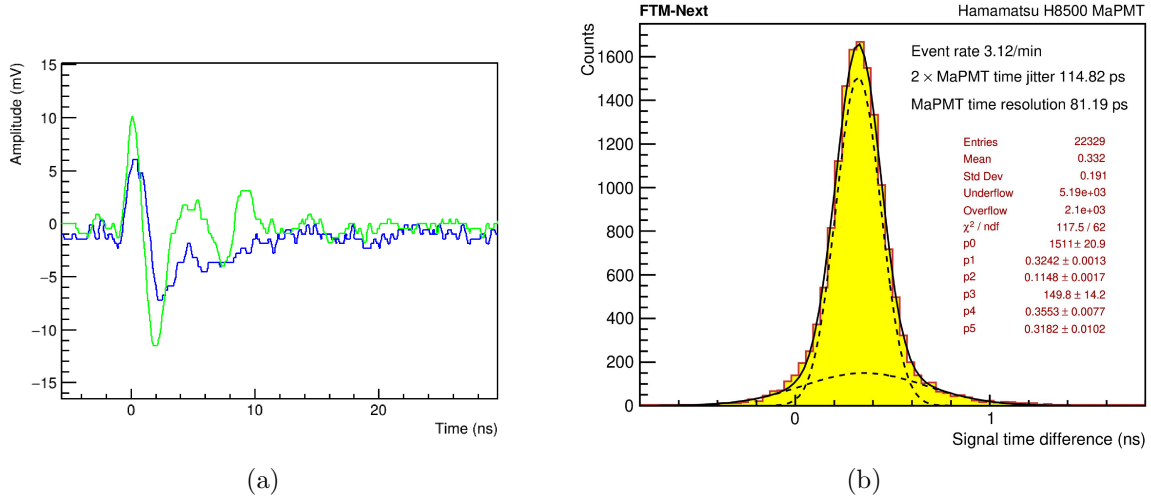


Figure 5.26: (a) Example of two MaPMT signals read out in coincidence. (b) Distribution of the difference between the signal arrival times of the two MaPMT signals, fitted with the sum of two gaussian functions.

[97]; SiPMs are arrays of single-photon avalanche diodes (SPADs), i.e. p-n junctions biased a few volts higher than the breakdown voltage that generate an avalanche in the depletion layer upon release of a charge carrier by a passing particle.

A scintillator read out with SiPMs has been assembled and tested with the goal of reaching time resolutions of the order of 100 ps as a time reference. A simple Geant4 [62] simulation has been developed with different input geometries to test the time resolution of different configurations; all geometries were made of a polyvinyltoluene plastic scintillator (with light yield 900 γ/MeV) coated with teflon wrapping of 99% reflectivity to ensure best light collection. The scintillator geometries simulated are a rectangular one of sides $1 \times 10 \times 0.5 \text{ cm}^3$ and a square one of side $10 \times 10 \times 0.5 \text{ mm}^3$ (Fig. 5.32a); the rectangular scintillator is read out by two SiPMs, one for each of the two small faces; each SiPM is has a surface of $3 \times 3 \text{ mm}^2$. The square scintillator is read out at two opposite faces, each coupled to five $3 \times 3 \text{ mm}^2$ equally spaced SiPMs.

The simulation was run with scintillation and optical processes enabled to trace the light collection at scoring volumes corresponding to the SiPM surfaces; a muon gun of vertical momentum and fixed energy of 5 GeV/c was used as generator. Fig. 5.32b shows an event display for 10 muon events in the rectangular scintillator. For each geometry the number of collected photoelectrons as a function of the position of passage of the muon was calculated, as shown in Fig. 5.33a; the signal arrival time at the readout was calculated as the collection time of the 50 first scintillation photons to reach the SiPMs. Fig. 5.33b shows the time of arrival of the signal as a function of the position of the muon hit in the scintillator; the time resolution of the detector was calculated as the RMS of the SAT distribution. The simulation results foresee a time resolution of 185 ps for the rectangular scintillator read out by one SiPM per face and 140 ps for the square scintillator read out by five SiPMs per face.

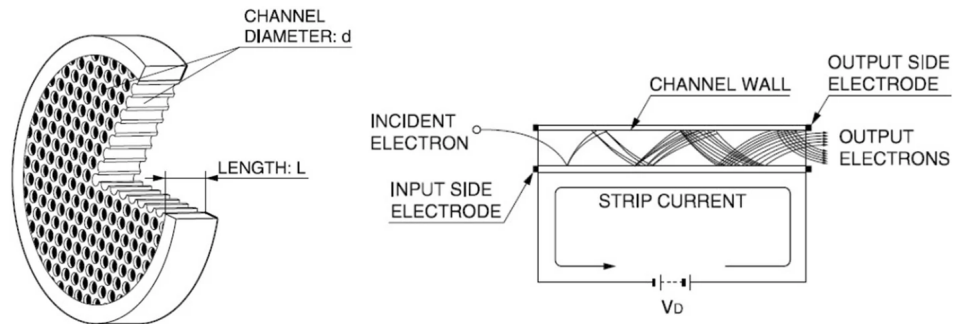


Figure 5.27: On the left, layout of a capillary plate photomultiplier; on the right, scheme of the electron amplification in a channel, from [94].

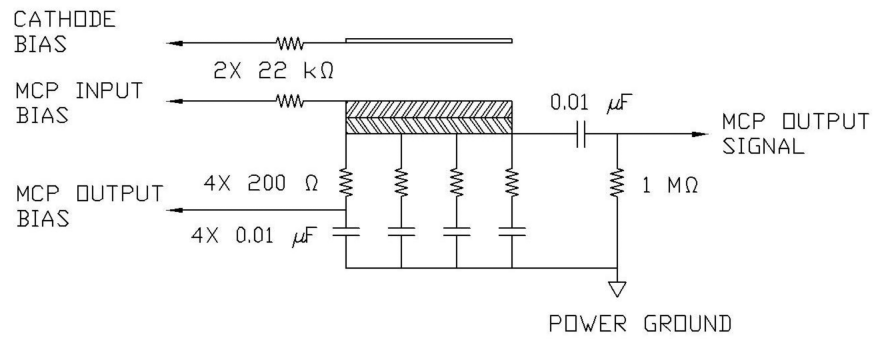


Figure 5.28: Layout and bias scheme of the Planacon XP85012 MCP-PMT, from [95].

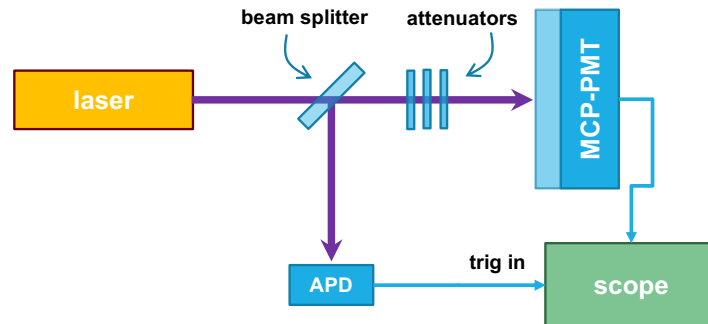


Figure 5.29: Setup for the MCP-PMT characterization with laser.

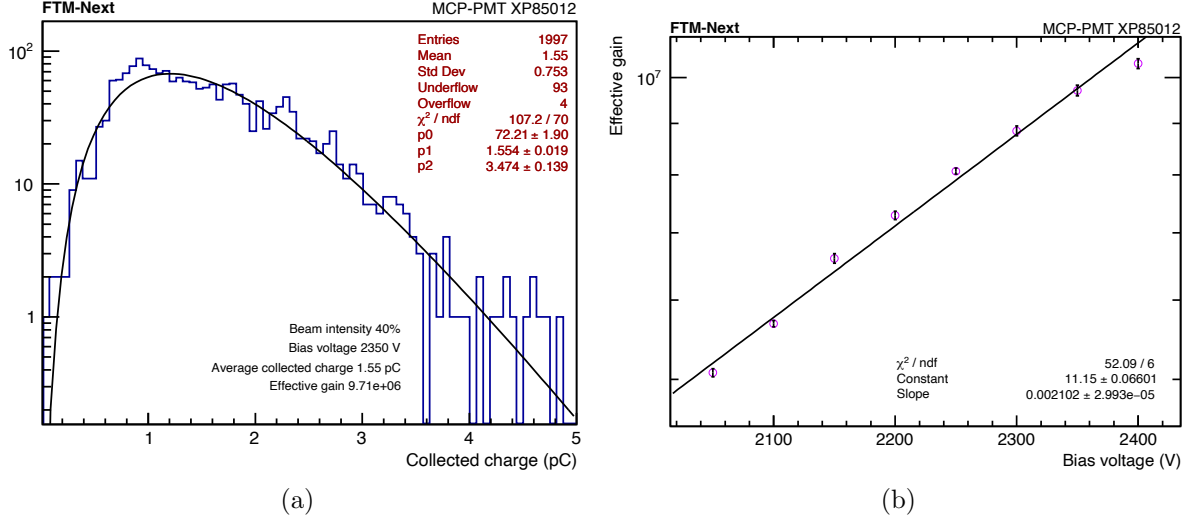


Figure 5.30: (a) Charge spectrum of the MCP-PMT response to UV laser in the single-photoelectron regime, fitted with a Polya distribution. (b) Measured gain of the MCP-PMT as a function of the bias voltage.

The rectangular geometry was tested on a BC-404 plastic scintillator of $1 \times 10 \times 0.5 \text{ cm}^3$ volume; the scintillator was coupled with two Hamamatsu 13360-3075PE [98] SiPMs, which have an active surface of $3 \times 3 \text{ mm}^2$, a pixel pitch of $75 \mu\text{m}$ and a breakdown voltage of $53 \pm 5 \text{ V}$. The average detection efficiency of the SiPMs is 50% for a wavelength between 320 and 900 nm. Each of the two SiPMs was biased and read out through the filter shown in Fig. 5.34 and the signals were saved on an oscilloscope.

The time resolution of the detector was measured in a test beam in the CERN North Area with 80 GeV/c muons, in a setup similar to the one already described for the MaPMTs. The time SiPMs were read out in coincidence with the Planacon MCP-PMT which was also used as time reference for the offline time resolution analysis.

Fig. 5.35 shows a recorded event in the timing measurement; the signal waveforms of the two SiPMs and the MCP-PMT were fitted with a sigmoid function and the signal arrival time was extracted as the time at 20% of the sigmoid amplitude. To correct for the time walk of the MCP-PMT, the trend of the MCP-PMT SAT as a function of the signal charge was fitted with a hyperbolic function of the form $t(q) = t_0 + k/q^\alpha$, as shown in Fig. 5.36. The time-walk compensated SAT t_c was calculated event by event from the measured arrival time t_m and the signal charge q_m as

$$t_c = t_m - k/q_m^\alpha,$$

where k and α are the fit result parameters.

Fig. 5.36 shows the distribution of the MCP-PMT signal charges and SATs after the time-walk compensation. Fig. 5.37 shows the signal arrival time distribution of the scintillator+SiPM system with respect to the MCP-PMT reference, calculated as

$$t_{\text{SiPM}} = \frac{1}{2}(t_{\text{SiPM } 1} + t_{\text{SiPM } 2}) - t_{\text{MCP-PMT}}$$

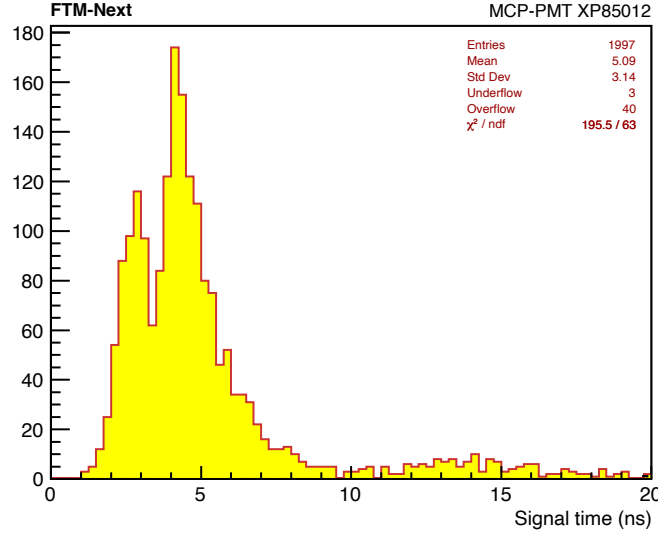


Figure 5.31: Signal arrival time distribution of the MCP-PMT irradiated by the laser in the single-photoelectron regime.

and fitted with the sum of two gaussian functions; the RMS time resolution is 578 ps, low enough for a time reference for an FTM with a low number of layers. The discrepancy from the simulated time resolution may be related to the several simplifications of the model, which neglects the dependency on the scintillation photon wavelength and the quantum efficiency of the SiPMs, as well as the contribution of the MCP-PMT time resolution which has not been measured directly.

5.8 Conclusion and outlook on future FTM development

The results shown above represent a new take in the early development of a fast timing MPGD; the goal of these measurements revolve around the three topics already mentioned in section 5.4:

1. assessing the performance of resistive foils;
2. verifying the signal induction and the detector transparency;
3. proving the FTM working principle by measuring the dependency of the time resolution by the number of layers.

While the latest goal – whose attainment also depends on the answer of the other two – still requires more work, the answer to the first two questions can help pointing in the right directions.

MPGDs embedding resistive elements are becoming more widespread especially by virtue of better intrinsic spark protection with respect to previous-generation technologies; the FTM stands somehow apart from other detectors of this category because it strictly allows only

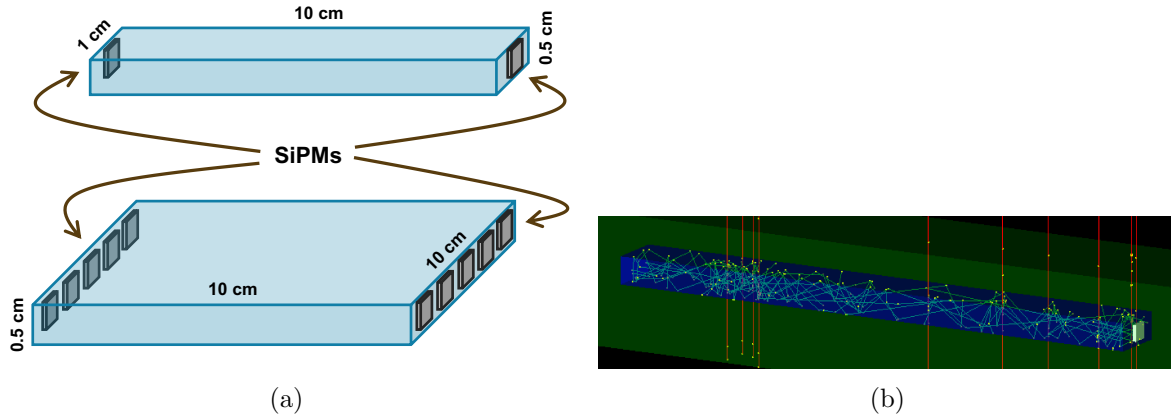


Figure 5.32: (a) Layout of the simulated rectangular and square geometries. (b) Simulated event display showing 10 muons passing through the rectangular scintillator.

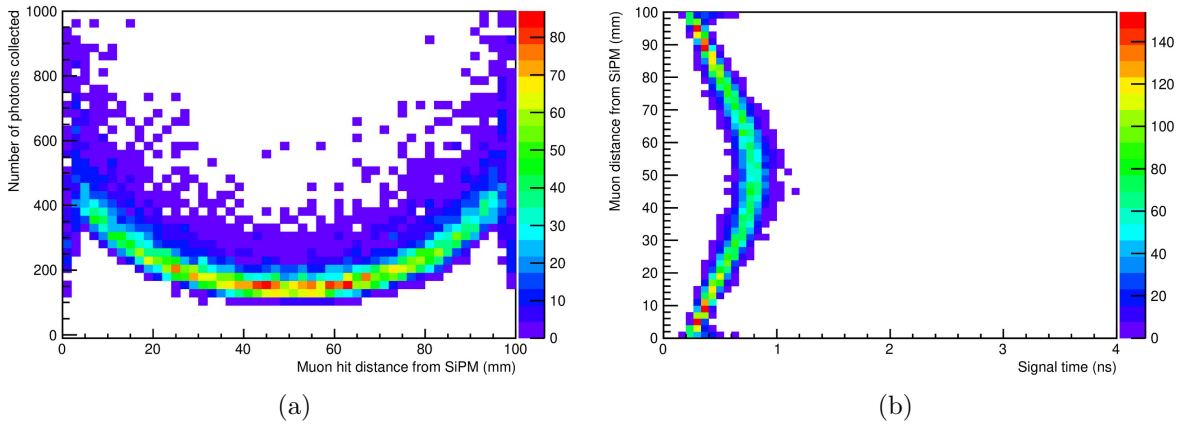


Figure 5.33: (a) Simulated distribution of the number of detected scintillation photons and the position of the muon hit. (b) Simulated distribution of the signal arrival time and the position of the muon hit.

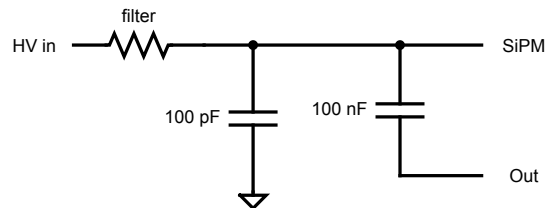


Figure 5.34: Bias and readout circuit for the SiPM, inspired from the design in [99]. The filter is an RC-RC with 1.2 k Ω resistors and 100 nF capacitors.

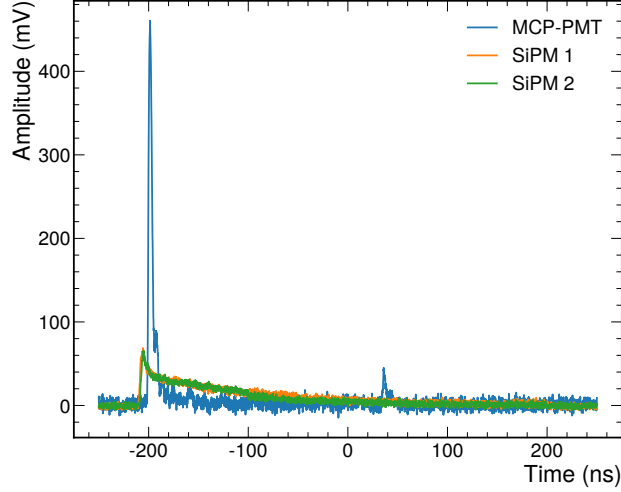


Figure 5.35: Event recorded on the oscilloscope showing the signals of the MCP-PMT and the two SiPMs.

resistive electrodes. The manufacturing of GEM-based amplification foils for the FTM is still a process under improvement: the etching of polyimide foils coated by DLC is sensitive to issues such as delamination due to imperfect DLC attachment, that reduce the foil stability and the maximum charge amplification. Although no systematic studies have been carried on the trend of the quality of DLC-coated foils over time, I have observed an apparent improvement in the performance while testing different batches of FTM foils: the effective gain reachable with the first FTM foils in 2019 was lower than 100 in Ar:CO₂, while the results obtained from the samples coated one year later improved on that by at least one order of magnitude.

At the present moment, the results from the previous sections show the present FTM foils reach gains comparable with or slightly lower than other MPGDs; the highest gain measured was 3×10^4 in Ne:iC₄H₈ 90%:10% – while values with any other mixture were lower by at least a factor 10. While this gain might be suitable for testing with a single layer, on a multi-layer FTM with thin gaps the primary charge is supposed to be much lower than in a classical MPGD – on average less than a single cluster; the amplification needed will be close to 10^5 , assuming the readout electronics is sensitive to input charges of the order of 1 fC. Therefore, more improvements on the foil quality are needed. The most reliable coating technique to date has been magnetron sputtering, while tests are ongoing on “home-made” foils produced by pulsed laser deposition. An important progress in this direction is the recent acquisition (in 2022) of the CERN-INFN DLC sputtering machine by the CERN MPT workshop, which is expected to allow faster rounds of testing between foil coating and etching to improve the sample adhesion and uniformity; the tests of the first FTM foils produced in the new facility are planned for the first half of 2023.

The second goal of the small-FTM testing, the transparency to readout signals, has been

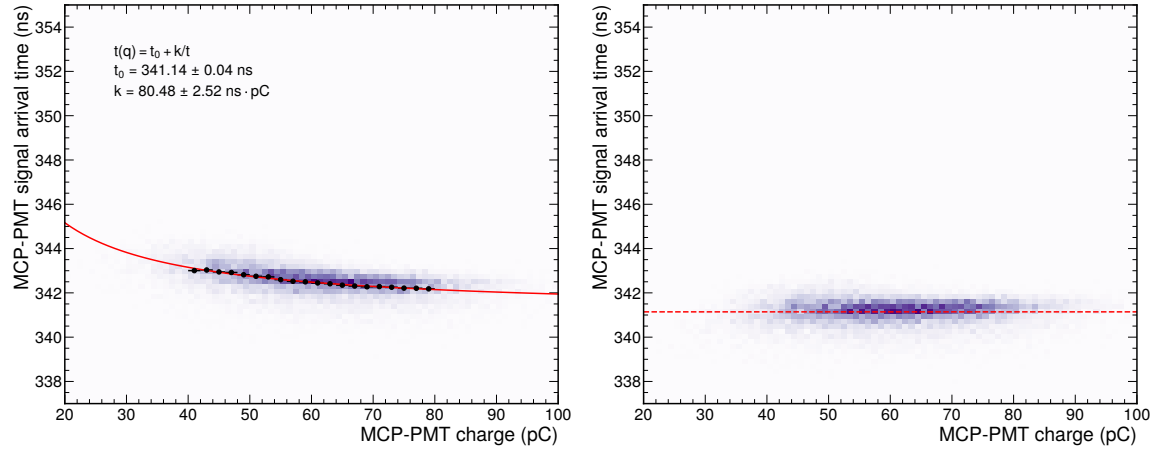


Figure 5.36: On the left, distribution of the MCP-PMT charge and signal arrival time fitted with a hyperbole. On the right, distribution of the charge and SAT after the time-walk compensation.

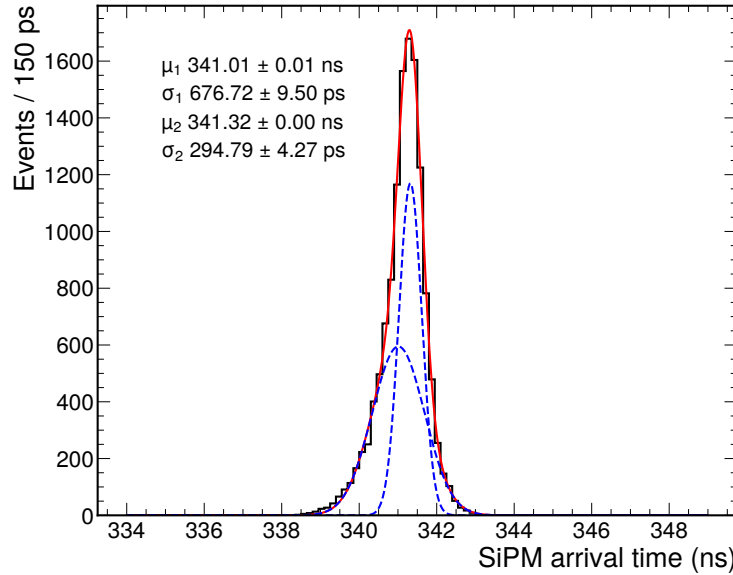


Figure 5.37: Distribution of the average between the two SiPM signal arrival times and the MCP-PMT. The fit is the sum of two gaussian functions.

shown with large charges through the simultaneous readout between the top and bottom pads; however, the presence of thin gaps (of a few hundred microns) between the bottom layer and the readout electrode – due to imperfect adhesion – has shown to strongly attenuate the readout signal. In this case the problem has been solved by glueing the two electrodes, which allowed recovering good efficiency to muons as shown in preliminary test beam results with a copper amplification foil; nonetheless, when multiple layers are added, the lower capacitance between the top layer and the readout might give rise to efficiency losses by a similar principle. This effect might pose a limit on the maximum thickness of the total detector volume and is an immediate point to be queried in the next tests.

Chapter 6

Conclusion

The work presented in this thesis has revolved on the development of MPGDs for the CMS upgrade and future collider experiments.

The two triple-GEM systems for the Phase-2 CMS upgrade will be installed by the end of the third Long Shutdown (LS3) of the LHC. The 2021 and 2022 test beams have shown the performance of the GE2/1 detectors is in line with or exceeds the GEM technical design report (TDR) expectations in terms of efficiency and space resolution; the integration with the final front-end electronics, in particular with the new VFAT3 plug-in card ASIC, has been completed. The detectors for the GE2/1 system are being produced and tested, with installation in CMS foreseen in the 2023/2024 extended year-end technical stop (EYETS).

The schedule for the production and installation of the ME0 detectors extends up to the end of LS3. Compared to GE1/1 and GE2/1, ME0 will face unprecedented challenges for a large-area MPGD system, mostly due to its intense background flux (up to 200 kHz/cm^2) with high rate disuniformity; the measurements described in this thesis have shown that the rate capability of a GEM detector in the baseline CMS design is limited by voltage drops in the protection circuits to rates of the order of 1 MHz per GEM foil sector. A gain recovery procedure has been defined and tested with x-rays; however, the issue of the high background disuniformity still required a change in the GEM foil layout by turning the baseline longitudinal GEM foil segmentation into an azimuthal one, which has been approved as the new ME0 GEM foil design.

The first ME0 prototypes with azimuthal segmentation have been produced and tested in test beam at the North Area to verify their operation, integration with the electronics and compliance with the TDR requirements. However, the final validation of the new design against high rate has only been tested recently in a test beam under irradiation at the GIF++, where the detector has been uniformly operated in background rates of tens of kHz/cm^2 and its efficiency has been measured with a triple-GEM tracker. The test beam results have shown an observable efficiency loss up to 5%, not compatible with the detector rate capability itself. An independent measurement with x-rays together with simulations of the VFAT3 have shown that the efficiency loss originated from the rate capability of the front-end electronics.

To assess the impact of the rate capability in the ME0 operations, a projection of the expected efficiency loss at the HL-LHC has been estimated. The efficiency loss has been

found of negligible effect on the performance of an ME0 stack thanks to the hit redundancy of the six layers; on this basis, a decision has been taken not to change the detector layout. However, a final confirmation that the efficiency loss of the full detector is not impacted will come from a test beam of an ME0 stack under irradiation; the assembly and integration of the first full ME0 stack is planned for the beginning of 2023.

The last topic faced in this thesis has been the development of the FTM, a MPGD designed for time resolutions below 1 ns based on a multi-layer resistive detector with amplification structure similar to the one of the μ -RWELL. The FTM working principle is not yet demonstrated; one of the goals of my activity has been determining the performance achievable with present resistive MPGDs and relate it to the FTM requirements. From a discussion of the history of past FTM prototypes, a set of constraints for a new one has been determined; the new detector has been assembled and tested with one layer to compare its amplification to a similar conductive layout and to find the gas mixture for best performance. The layout of the detector was then optimized to increase the readout efficiency. Finally, a version of the prototype instrumented with a conductive foil has been operated in test beam.

The studies on the FTM have shown that despite recent improvement the present generation of resistive amplification foils cannot ensure sensitivity to single primary electrons, which would require achieving gains of $\sim 10^5$ and are needed for a multi-layer FTM with thin drift gaps; however, the increasing interest in the MPGD community for new techniques of coating and etching of resistive materials is pointing in the right direction. The FTM development is expected to take advantage over the next years from the improvement of resistive coating adhesion, uniformity over large area and tuning of resistivity.

Appendix A

GEM foil manufacturing with random hole sectorization

The presence of the sectorization of the GEM foils poses two potential issues related to the ease of manufacturing and to the uniformity of the detector efficiency.

Fig. A.1b shows a region of an ME0 detector GEM foil manufactured with a standard technique (“blank” segmentation) containing the separation between two sectors observed with a microscope. In a GE2/1 detector (Fig. A.1a) the sector separation line is parallel to the pattern of the GEM holes, while in a second-generation ME0 detector the sectorization is oblique with respect to the hole pattern; in the latter case a higher precision is needed in the alignment of the photoresist mask with the hole pattern and the procedure is more sensitive to error.

The foil sectorization introduces a dead area in the detector, i.e. a region with distorted electric field lines in the gas due to the absence of GEM holes. This is a more relevant issue for ME0 than for GE2/1, because of the higher number of sectors and the dead area due to the oblique segmentation is larger (between 400 and 600 μm , while it is about 200 μm in GE2/1). The resulting dead area is of approximately between 4 and 6% – depending on the position along η of the total detector surface for ME0, while the dead area of a GE2/1 detector amounts to only 2%.

The two issues arise during the production of segmented GEM foils: before the kapton etching, the segmentation is part of the mask applied on the photoresist layer so that the segmentation region does not present itself as covered by holes; after the kapton etching, the copper is removed in correspondence to the desired segmentation with a second mask – which needs to be aligned with the first one – and a second etching round. therefore, a possible solution consists of not embedding the segmentation pattern in the first mask and carrying the copper etching without excluding any region from the hole pattern. Fig. A.2 shows a foil obtained with this new process, called “random hole” sectorization. The hole pattern is not interrupted in correspondence to the polyimide line that separates the two sectors; a few holes are cut by the sectorization line.

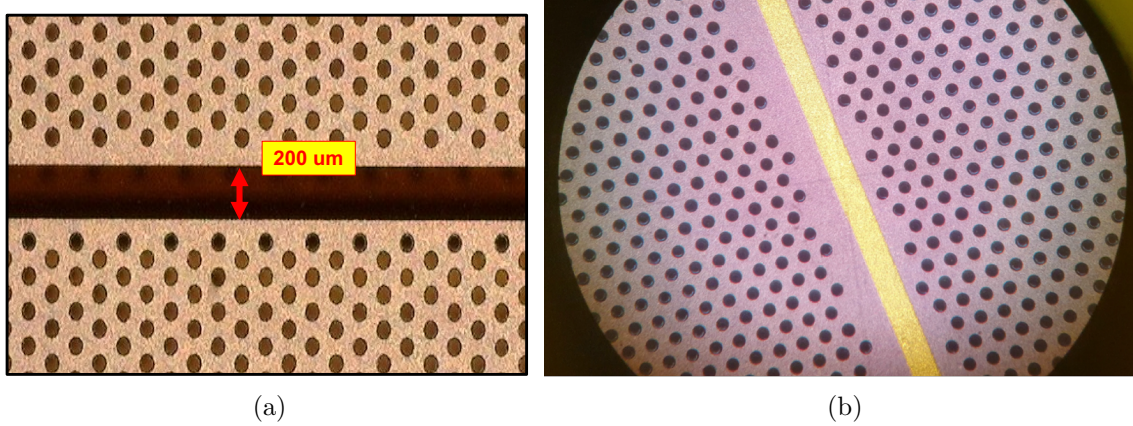


Figure A.1: Region of a GE2/1 foil (a) and an ME0 foil (b) containing the separation between two sectors.

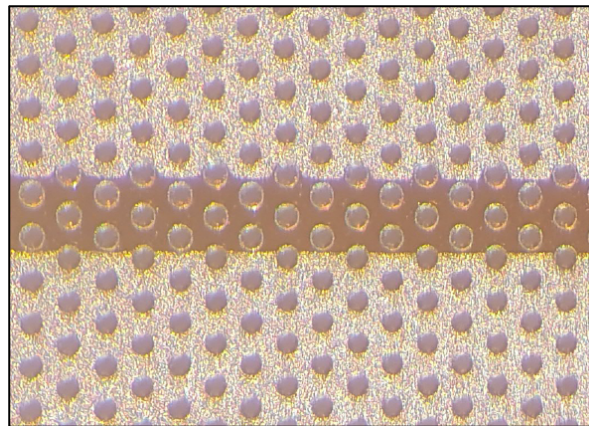


Figure A.2: Microscope picture of part of a GEM foil produced with random hole segmentation.

A.0.1 Production steps for random-hole segmentation

The detailed steps for the production of GEM foils with random hole segmentation using the single-mask technique are represented in Fig. A.3:

- a) the production starts from a 50 μm thick polyimide (PI) foil covered by two 5 μm thick copper layers;
- b) two photoresist layers are applied on top and bottom;
- c) a mask with the hole pattern is applied on the top photoresist layer; in the blank segmentation foil production, this mask also presents the segmentation pattern;
- d) the mask is exposed to UV light and the pattern is developed on the top photoresist;

- e) the copper is etched in a chemical bath;
- f) the photoresist is removed;
- g) the PI is etched from the top giving rise to a conical hole pattern;
- h) the bottom copper layer is laminated by a protective layer;
- i) the bottom copper layer is etched;
- j) the resist layer is removed;
- k) the polyimide is etched from the bottom layer, leaving double-conical holes;
- l) to apply the segmentation, the foil is covered again by a photoresist layer on both sides;
- m) a mask with the segmentation pattern is applied; since the original mask at step c) did not have a segmentation pattern, no alignment is required and the mask may also cut a GEM hole. This step is also followed in the blank segmentation production, but the segmentation mask would need to be aligned with the pattern already present in the foil;
- n) the mask is developed, leaving the copper exposed;
- o) the copper in the segmentation zones is etched, leaving the polyimide exposed;
- p) the photoresist is removed.

A.0.2 Applications of random-hole segmentation

The first tests with detectors manufactured with the random-hole sectorization technique were performed at CERN by the gas detector development group (GDD) in 2020 [101]; optical measurements on the foils of the first prototypes showed the transparency of a random-hole segmented foil in the separation between two sectors to be higher than a blank-segmented foil. However, such foils showed electrical instabilities when supplied with high voltage, presumably due to delamination of copper in the sharp edges of the GEM holes that were cut in half by the segmentation; no measurements were carried out on the performance of such first prototypes.

The manufacturing of foils with random-hole segmentation has been reconsidered for the high-rate R&D for the ME0 detector; with the advancements of the etching techniques of the latest years, especially with the progresses in the now widely-used single-mask technique, the production of a random-hole segmented GEM foil has been found free of the stability issues of the first samples, as shown in the laboratory characterization of the first recent prototypes [58]. At the moment, blank-segmented GEM foils are the baseline solution for the production of all CMS GEM detectors; nevertheless the 2021 and 2022 test beam have included as well random-segmented detectors to demonstrate their operation in particle beam and compare their performance with the blank-segmented detectors.

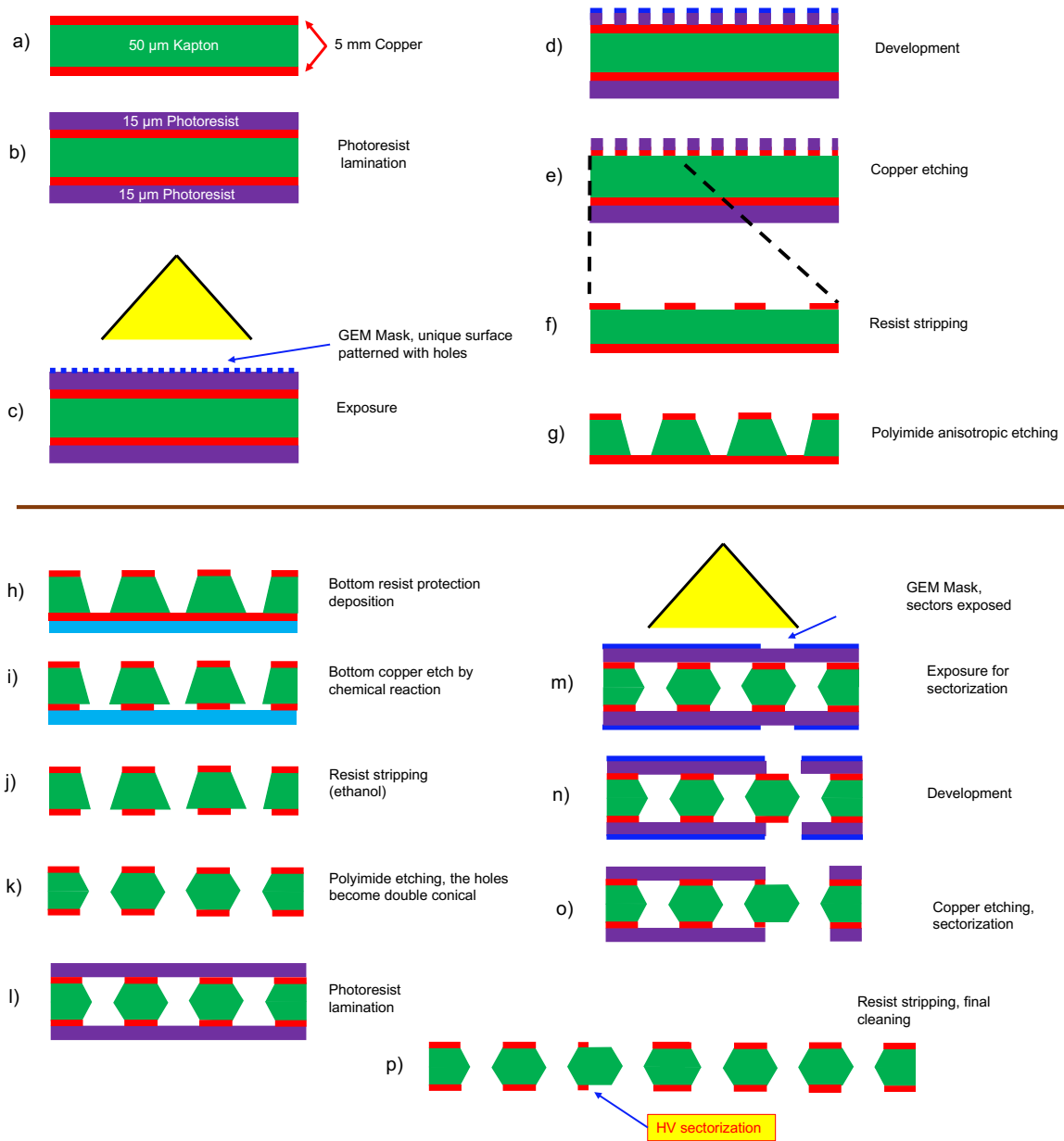


Figure A.3: Production steps for a GEM foil with random hole segmentation [100].

Appendix B

Front-end dead time and detector dead time

The GIF++ test beam results showed that the ME0 detector operated in a intense background environment with the GIF++ source has an efficiency for muons compatible with a dead time of 90.7 ns; simulations and measurements with x-rays have shown that the VFAT3 dead time, depending on the input charge, is comprised between 200 and 1000 ns (see Sec.4.6.3). A numerical simulation has been developed to understand how the detector dead time can be related to the strip dead time by keeping into account the effect of the cluster size of the background hits.

The toy monte carlo works by generating events hitting a detector surface made of 384 rectangular parallel strips (equal to the number of strips per η partition in an ME0 detector) uniformly in space and with an average rate of 250 kHz per strip; the area of the detector does not matter in the simulation. Each event contains one hit; the hits are generated by sampling a random time from a Poisson distribution with mean $\tau = (250 \text{ kHz} \times 384)^{-1}$ and the central strip hit from a uniform distribution; the distributions of the generated events in time and space are shown in Fig.B.1.

For each event, the corresponding hit is digitized by assuming a fixed cluster size 3; after the digitization, the distribution of the signal arrival times for each strip are calculated as a cross-check. Fig.B.2 shows the distributions of the signal arrival times for all hits, showing that the average rate is approximately 250 kHz as expected.

A dead time $t_0 = 400 \text{ ns}$ is applied through the following procedure:

- for each strip, an event is marked as “not detected by the strip” if its distance from the previous hit occurring on the same strip is lower than t_0 ;
- an event is marked as “not detected by the detector” if it is not detected by any of the strips it hits.

After applying the selection, the following two variables are calculated:

- the efficiency of the strip is defined as the ratio between the number of events detected by the strip and the number of events containing a hit on the strip;

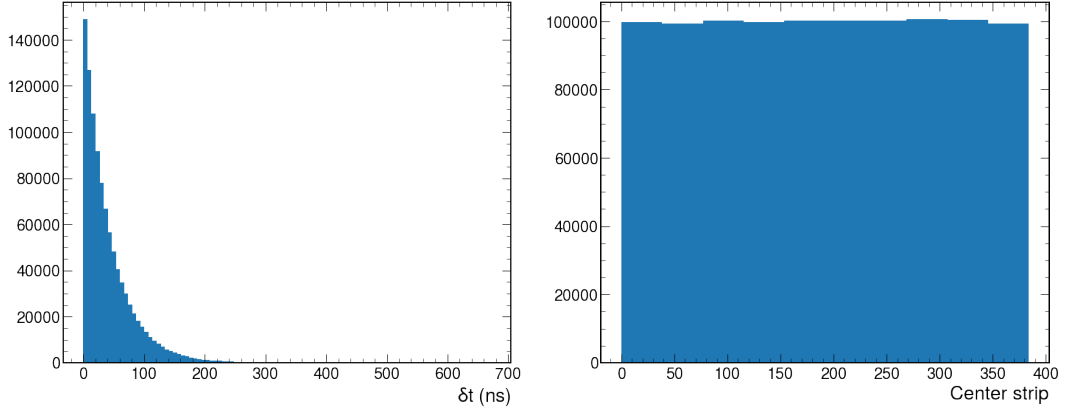


Figure B.1: Distribution of the distances in time between consecutive generated events (left) and distribution of the central strip of the generated events (right).

- the efficiency of the detector is defined as the ratio between the number of events detected by the detector and the total number of events.

The procedure above defined is repeated for different input rates per strip; Fig. B.3a shows the trend of the strip efficiency (averaged among all the strips) and the detector efficiency as a function of the input rate. The trends are fitted by the function:

$$\epsilon = \frac{1}{1 + f\tau},$$

to determine the measured “strip” and “detector” dead times. The calculated strip dead time of 426.1 ± 4.3 ns is close to the input dead time of 400 ns, while the detector dead time is much lower, equal to 155.1 ± 2.9 ns. The behaviour is confirmed by the trend of the measured strip and detector dead times as a function of the input dead time (Fig. B.3b).

An intuitive explanation for having a detector dead time larger than the strip dead time can be stated as follows: during the time interval in which a strip is inactive, an event that hits it may still be correctly detected by the detector since it will be detected by the neighbouring strips. A quantitative comparison between these considerations and the ME0 test beam results would depend on the knowledge of background charge spectrum and the cluster size distribution.

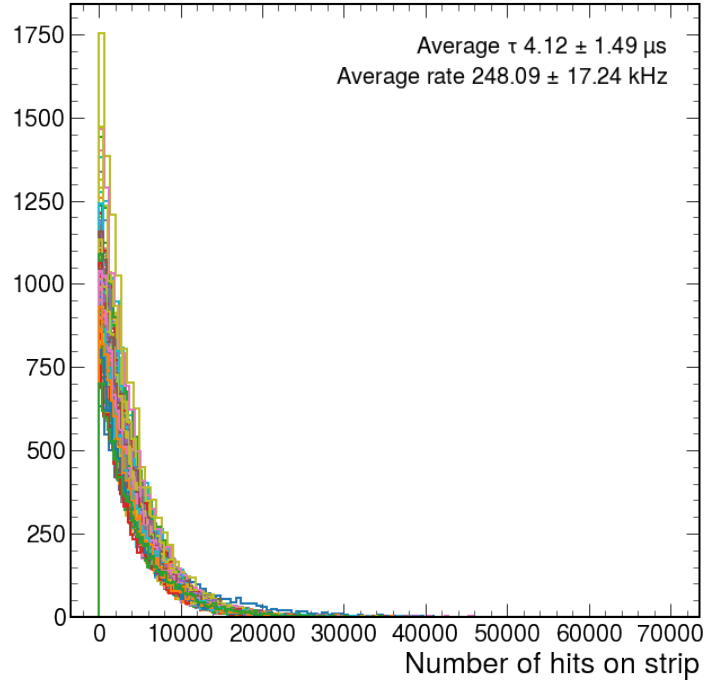
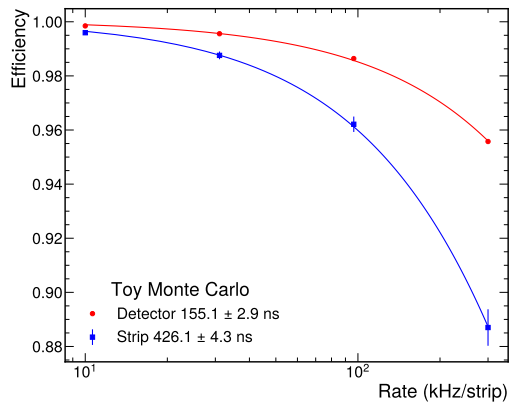
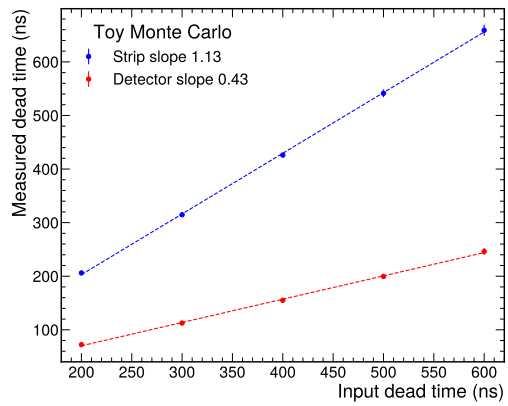


Figure B.2: For each strip, distribution of the distances in time between consecutive hits; the average of the distribution and its inverse (i.e. the average rate) are shown.



(a)



(b)

Figure B.3: (a) Strip and detector efficiency scan as a function of the input rate per strip. (b) Measured strip and detector dead times as a function of the detector dead time.

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