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**Development and characterization of the Fast
Timing Micro-Pattern Gaseous Detector**

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Introduction

Gaseous detectors have proven to be a versatile and cost effective technology for several large High Energy Physics (HEP) experiments, as well as for applications beyond fundamental particle physics, such as medicine, astrophysics and material analysis. With the invention and evolution of Micro Pattern Gaseous Detectors (MPGDs) during the last twenty years, gaseous detectors improved significantly in spatial resolution and rate capability. MPGDs were in fact conceived in order to overcome the limitations of the Multi-Wire Proportional Chamber (MWPC) with respect to position resolution and their capability to cope with high particle fluxes and long-term stability. Today, Gas Electron Multiplier (GEM) and MICRO-MESh Gaseous Structure (Micromegas) are the most common MPGD devices.

Since the time resolution of Micro Pattern Gaseous Detectors is limited by the statistics of ion-pair production to few ns, the development of fast timing, high-rate capable MPGDs with high spatial and energy resolution is a challenging target for researchers in different fields (from HEP to medical physics). In this thesis a new prototype of Fast Timing MPGD (FTM) will be developed, together with the tests of its dedicated readout electronics. The prototype has been characterized using x-rays. Since the amplification structure inherits the perforated kapton foil of a Gas Electron Multiplier (GEM), a single GEM has been used as a benchmark for these measurements.

Chapter 1 provides the basic concepts of radiation-matter interaction for the detection of charged particles and photons and gives an overview on the most important gaseous detectors.

In Chapter 2 the working principles of the FTM detector are presented. Both the existing and the new FTM prototypes are described.

Chapter 3 reports the experimental procedures employed to test a single-GEM detector, used as a benchmark for the characterization of the FTM.

In Chapter 4 the results of the preliminary tests performed on the FTM v.4 prototype are shown. Moreover, the limitations of the test setup are discussed and some upgrade ideas are presented.

Finally, Chapter 5 is dedicated to the characterization of the FATIC readout chip, which was developed for the acquisition of the FTM signals.

Chapter 1

Gaseous Detectors

Gaseous detectors are instruments capable of detecting and amplifying the ionization charge produced by a particle crossing a gaseous volume. The detection process typically consists of two stages, named *drift* and *amplification* and the zones where they take place are not necessarily separated. In the drift zone, the incoming particle interacts with the gas atoms or molecules and can produce some electron-ion pairs, which move driven by an electric (drift) field and reach the amplification zone. Here, the charges are accelerated by an intense electric field and gain sufficient energy to further ionize the gas; the number of ionizations grows exponentially, resulting in a electron-ion avalanche that induces a significant signal on the readout electrodes.

The working principles of gaseous detectors will be treated in this chapter: the first section gives an overview of the interaction of charged particles or photons with matter; in the second part the transport and amplification of charge within gaseous detectors are described. The third part focuses on Micro Pattern Gaseous Detectors (MPGDs), with particular attention to Gas Electron Multiplier (GEM) detectors.

1.1 Radiation-Matter Interactions

The section summarizes the relevant theory needed to describe the interactions of radiation with matter and it is adapted from Knoll (2000 [1]) and Sauli (2014

[2]). Further sources are explicitly cited.

1.1.1 Interaction between charged particles and matter

Charged particles interact with matter primarily through electromagnetic interaction with the electronic cloud of the atoms, although interactions with nuclei are also possible. Except for particles approaching the end of their *range*, where elastic collisions are relevant, the slowing down in matter is mainly due to multiple processes of excitation and ionization, whose probability is a function of the energy transfer.

Energy loss for heavy particles

From now on we will distinguish between electrons and heavy charged particles (i.e. with a mass much greater than the electron mass, such as muons, protons, alpha particles). The maximum energy that can be transferred from a heavy charged particle of mass M with kinetic energy E to an electron of mass m_e in a single collision is $4 \cdot E \cdot m_e/M$. For heavy particles it is a small fraction of the initial energy, so that the incident particle will slow down going through the medium after a large number of interactions. The differential energy loss due to multiple Coulomb interactions is given by the *Bethe formula*:

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 Z n}{m_e v^2} \left[\ln \frac{2m_e v^2}{I_0} - \ln(1 - \beta^2) - \beta^2 \right] \quad (1.1)$$

where ze is the charge of the primary particle, v is its velocity, $\beta = \frac{v}{c}$, n and Z are the number density and the atomic number of the atoms in the medium, m_e is the electron mass, I_0 is the average excitation and ionization energy of the absorber medium. The second and third terms in the formula 1.1 are the relativistic corrections to the first formulation (Bethe 1930) and they are not relevant for $\beta \ll 1$. Therefore, the *Bethe formula* is based on the assumption that the charged particle velocity is significantly larger than the one of the atomic electrons. The values of useful physical parameters for typical gas mixtures used in gaseous detectors at normal temperature and pressure (NTP, 20°C and 1 atmosphere) can be found in Table 1.1.

Table 1.1: Properties of gases commonly used in gaseous detectors: atomic number Z , atomic weight A , density, mean excitation potential I_0 , average energy to produce an electron-ion pair W_i , energy loss dE/dx , and number of primary and total electron-ion pairs n_p and n_{tot} per unit length. Energy loss and numbers of electron-ion pairs are given at atmospheric pressure for minimum ionizing particles. Values of n_p shown in brackets are estimated from the linear dependence of n_p on the atomic number Z [3].

Gas	Z	A	Density (g/cm ³)	I_0 (eV)	W_i (eV)	$\rho^{-1} \cdot dE/dx$ (MeV/g cm ²)	dE/dx (MeV/cm)	n_p (cm ⁻¹)	n_{tot} (cm ⁻¹)
H ₂	2	2	$8.38 \cdot 10^{-5}$	15.4	37	4.03	0.34	5.2	9.2
He	2	4	$1.66 \cdot 10^{-4}$	24.6	41	1.94	0.32	5.9	7.8
N ₂	14	28	$1.17 \cdot 10^{-3}$	15.5	35	1.68	1.96	(10)	56
O ₂	16	32	$1.33 \cdot 10^{-3}$	12.2	31	1.69	2.26	22	73
Ne	10	20.2	$8.39 \cdot 10^{-4}$	21.6	36	1.68	1.41	12	39
Ar	18	39.9	$1.66 \cdot 10^{-3}$	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	$3.49 \cdot 10^{-3}$	14.0	24	1.32	4.60	(22)	192
Xe	54	131.3	$5.49 \cdot 10^{-3}$	12.1	22	1.23	6.76	44	307
CO ₂	22	44	$1.86 \cdot 10^{-3}$	13.7	33	1.62	3.01	(34)	91
CH ₄	10	16	$6.7 \cdot 10^{-4}$	13.1	28	2.21	1.48	16	53
C ₄ H ₁₀	34	58	$2.42 \cdot 10^{-3}$	10.8	23	1.86	4.50	(46)	195

Radiative energy loss mechanisms, such as *bremsstrahlung*, are only relevant at very high energies: an example of the average energy loss for positive muons in copper as a function of $\beta\gamma = p/Mc$ is illustrated in Figure 1.1, which shows the radiative contribution to the total energy loss.

Energy loss for light particles

Like heavy particles, beta particles (i.e. electrons and positrons) can excite and ionize the atoms passing through a medium, but they can lose a large fraction of their energy in a single collision with an atomic electron, which has equal mass. Beta particles differs from heavy charged particles in that they can significantly radiate energy by *bremsstrahlung*, while the yield of *bremsstrahlung* for heavy particles is negligible. An expression similar to Eq. 1.1 has been derived by Bethe to describe the specific energy loss due to ionization and excitation for electrons. It takes into account that an incoming electron is indistinguishable from the atomic

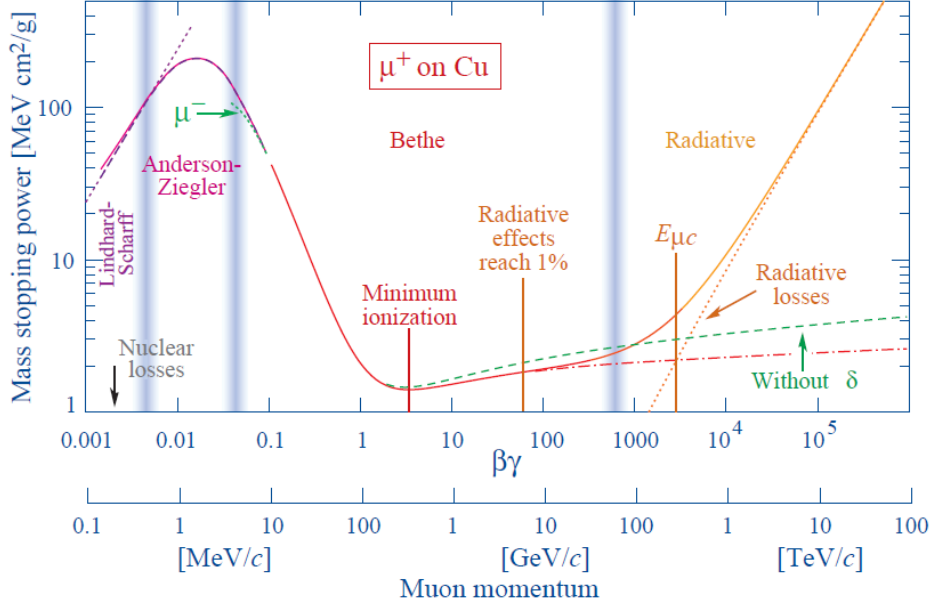


Figure 1.1: Mass stopping power ($= \langle dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum. Solid curves indicate the total stopping power. dE/dx in the radiative region is not simply a function of β . [4]

electron with which it collides and it contains relativistic corrections:

$$\begin{aligned}
 -\left(\frac{dE}{dx}\right)_c &= \frac{2\pi e^4 n Z}{m_e v^2} \left[\ln \frac{m_e v^2 E}{2I^2 (1 - \beta^2)} + A + B \right] \\
 A &= -(\ln 2) \left(2\sqrt{1 - \beta^2} - 1 + \beta^2 \right) \\
 B &= + (1 - \beta^2) - \frac{1}{8} \left(1 - \sqrt{1 - \beta^2} \right)^2
 \end{aligned} \tag{1.2}$$

the notation is the same used in Eq. 1.1. At energies of a few 10's of MeV, radiative processes become more important than ionization. The average energy loss $\frac{dE}{dx}$ is a combination of various effects such as e^+e^- pair production, Bremsstrahlung and photo-nuclear interactions. The following formula gives the linear specific energy loss through radiative processes and it is calculated from classical electrodynamics:

$$-\left(\frac{dE}{dx}\right)_{rad} = \frac{e^4 E n Z (Z + 1)}{137 m_e^2 c^4} \left(4 \ln \frac{2E}{m_e c^2} - \frac{4}{3} \right) \tag{1.3}$$

The total energy loss for electrons is the sum of radiative and collisional losses.

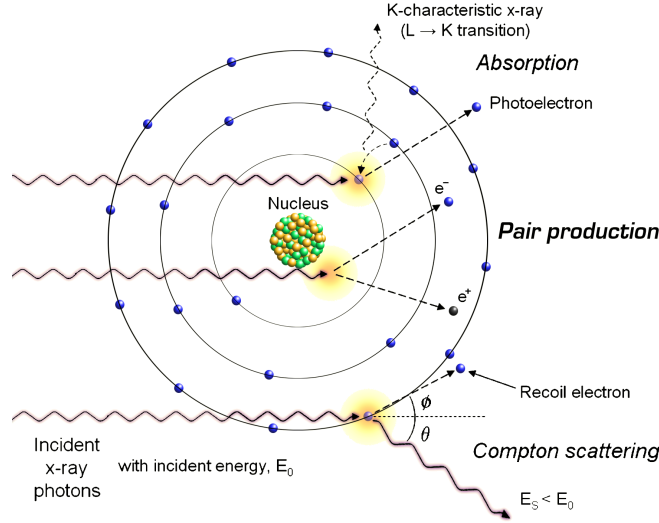


Figure 1.2: Main atom-photon interaction mechanisms.

1.1.2 Interaction between photons and matter

The relevant interaction mechanisms for photons in matter are *photoelectric absorption*, *Compton scattering* and *pair production*; they are shown in Figures 1.2 and 1.3. In contrast to what happens for charged particles that slow down through multiple collisions, photons are involved in *destructive* interactions, since the incoming photon is completely absorbed as a consequence of a single encounter. The probability of interaction for the different mechanisms is strongly energy-dependent: Figure 1.4 shows the cross sections for photons in argon and carbon dioxide as a function of the photon energy.

The absorption of a mono-energetic beam of photons by a uniform layer of material of thickness x is described by an exponential law:

$$I = I_0 \cdot e^{-\mu \rho x} \quad (1.4)$$

where I_0 is the initial intensity of the photon beam, I is the intensity of the outcoming beam, ρ is the density of the material and μ is called the *mass absorption coefficient*.

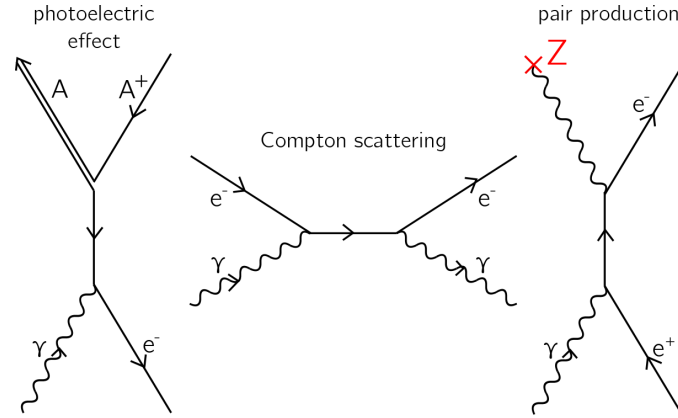


Figure 1.3: First order Feynman diagrams of atomic photoelectric absorption, Compton scattering and pair production.

Photoelectric absorption

In the photoelectric absorption process, an incoming photon is fully absorbed by an atom and an energetic *photoelectron* is ejected from an atomic shell. The energy of the photoelectron is given by:

$$E_{e^-} = h\nu - E_b \quad (1.5)$$

where E_b is the binding energy of the electron and $h\nu$ is the initial energy of the photon. Because of the momentum conservation, the photoelectric effect cannot occur with free electrons and always involves the whole atom. The interaction cross section depends on the photon energy and on the atomic electron configuration: for photons whose energy is above the highest electron binding energy (the K shell), the cross section is relatively small and the most probable origin of the photo-electron is the K shell. As the photon energy decreases, the cross section has a peak corresponding to the K shell energy and drops (K absorption edge) until the energy of the next shell (L) is reached. At low energy, the photoelectric cross section has several peaks which correspond to the L, M, N transition energies.

After the interaction, the absorber atom has a vacancy that is quickly filled by an electron from a higher shell or by capture of a free electron. This rearrangement leads to the emission of the excess energy as a *fluorescence* photon (X-ray). In most cases these X-rays are reabsorbed through photoelectric interaction involving

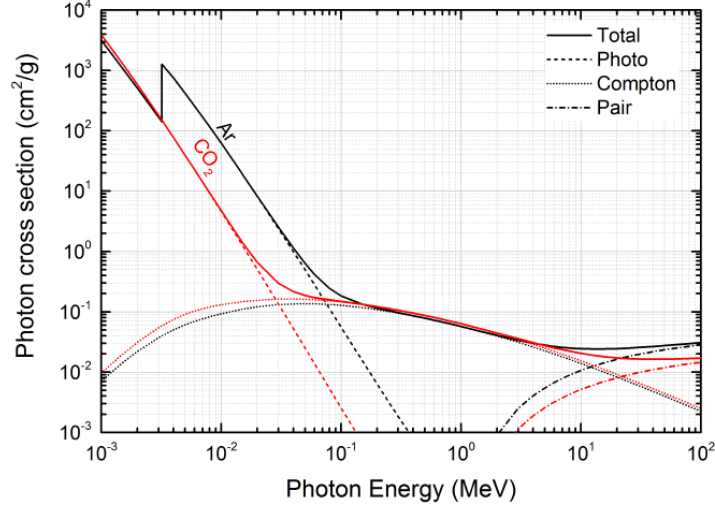


Figure 1.4: Photon cross section for Ar and CO₂ for different interaction mechanisms [5].

external atomic shells. An alternative effect to the emission of fluorescence photons is the *Auger emission*, in which the excess energy of the electron filling the vacancy is absorbed by a second electron on a lower energy level, which is ejected (*Auger electron*).

The photoelectric effect is the dominant interaction mechanism for low energy photons (< 100 keV) and it is enhanced for high Z materials. The cross section calculation requires a quantum-relativistic discussion and does not give an unique expression for different values of the photon energy. However, at MeV energies an approximate dependence of the photo-electric absorption probability on the atomic number of the medium is given by:

$$\sigma \propto Z^n \quad (1.6)$$

where n varies in the range $[4; 5]$ depending on the photon energy.

Compton scattering

Compton scattering is an inelastic interaction that involves an incident photon and an electron in the medium. The photon interacts with the electron, which is assumed to be initially at rest, and it is scattered at an angle θ with respect to its

initial direction. The energy of the outgoing photon is given by:

$$h\nu' = \frac{h\nu}{1 + h\nu(1 - \cos\theta) / (m_0c^2)} \quad (1.7)$$

where m_0c^2 is the electron rest-mass energy (0.511 MeV). The energy of the *recoil* electron is

$$E_{e^-} = h\nu - h\nu' \quad (1.8)$$

The Compton interaction probability depends on the electron density of the medium, so it increases linearly with the atomic number of the material (Z). The angular distribution of the scattered photons is given by the *Klein-Nishina formula* for the differential cross section:

$$\frac{d\sigma}{d\Omega} = Zr_0^2 \left(\frac{1}{1 + \alpha(1 - \cos\theta)} \right)^2 \left(\frac{1 + \cos^2\theta}{2} \right) \left(1 + \frac{\alpha^2(1 - \cos\theta)^2}{(1 + \cos^2\theta)[1 + \alpha(1 - \cos\theta)]} \right) \quad (1.9)$$

where r_0 is the classical radius of the electron and $\alpha = h\nu/m_0c^2$. Figure 1.3 shows one of the first order Feynman diagrams describing the process. Compton scattering is the dominant process for photons whose energy is above the highest electron shell level and lower than 10 MeV.

Pair production

The electron-positron production is the dominant mode of interaction between photons and matter and it can occur if the photon energy is above the sum of the rest mass energies of an electron and positron ($E_{thr} = 2m_e c^2 = 1.022$ MeV). In the strong Coulomb field of the nucleus the photon can be absorbed, producing an electron-positron pair. Although the nucleus receives some recoil energy, the excess photon energy can be considered to be completely transferred to the produced particles. The pair-production cross section can be calculated from quantum-electrodynamics using the Feynman diagram shown in Figure 1.3 and it is proportional to Z^2 , where Z is the atomic number of the medium.

1.2 Working principles of Gaseous Detectors

The first part of this section discusses the creation, transport and amplification of charges within gaseous detectors and it is mainly adapted from Sauli (2014 [2]). The principles of signal induction are then treated and the necessary calculations are taken from Blum - Reigler (2008 [8]).

1.2.1 Ionization

On the passage of a charged particle through the gas volume, a number of ionizing interactions takes place, resulting in the creation of *primary* electron-ion pairs. The electron ejected from the interacting atom can have enough energy to cause further ionizations and create *secondary* electron-ion pairs. The total number of pairs produced per unit length is given by:

$$n_{\text{tot}} = \frac{\Delta E}{W_i} \quad (1.10)$$

where ΔE is the total energy released by the ionizing particle in the gas volume and W_i is the average energy to produce an electron-ion pair. Values of W_i for different gases are reported in Table 1.1. The table shows also the number of primary ionizations per unit length (n_p) for different gases, which turns out to be roughly linearly dependent on the average atomic number of the gas (Z). It is useful to calculate n_{tot} and n_p produced by a MIP in the gas mixture Ar/ CO_2 70/30 at normal conditions, since it is frequently used in gaseous detectors:

$$n_{\text{Tot}} = \left(\frac{dE}{dx} \Big|_{\text{MIP in Ar}} / W_{i\text{Ar}} \right) \cdot 0.7 + \left(\frac{dE}{dx} \Big|_{\text{MIP in CO}_2} / W_{i\text{CO}_2} \right) \cdot 0.3 \simeq 93 \text{ cm}^{-1} \quad (1.11)$$

$$n_p = n_{p,\text{Ar}} \cdot 0.7 + n_{p,\text{CO}_2} \cdot 0.3 \simeq 31 \text{ cm}^{-1} \quad (1.12)$$

The primary ionizations distributed along the particle path can be considered independent random events, whose distribution can be described as a Poisson point process. The probability that k primary ionizations occur along the normalized path $[0; 1]$, if n is the average number of primary pairs produced, is given by the Poisson distribution:

$$p(k, n) = \frac{(n)^k}{k!} e^{-n} \quad (1.13)$$

Instead, the spatial (or temporal) distance Δx between two successive events is exponentially distributed:

$$P(\Delta x, n) = ne^{-n\Delta x} \quad (1.14)$$

The maximum efficiency of an ideal gaseous detector filled of Ar/CO₂ 70/30 with thickness $d = 1$ mm can be estimated as follows:

$$\varepsilon = 1 - p(0, n_p d) = 1 - e^{-n_p d} = 1 - e^{-31 \text{cm}^{-1} \cdot 0.1 \text{cm}} \simeq 95.5\% \quad (1.15)$$

where $n_p \cdot d$ is the average number of primary ionizations produced by a MIP passing across the full thickness d of the gas volume, at standard temperature and pressure conditions.

1.2.2 Diffusion and drift

The electron-ion pairs produced along the ionizing particle path can recombine or move in the gas medium, depending on their initial energy and on the presence of an external electric or magnetic field. In the absence of an external field, the primary electrons and ions lose their energy by multiple collisions with the gas atoms and reach the thermal equilibrium. Their energy distribution is described by the *Maxwell-Boltzmann law*:

$$F(\epsilon) = 2 \left(\frac{\epsilon}{\pi(kT)^3} \right)^{\frac{1}{2}} \exp \left(\frac{-\epsilon}{kT} \right) \quad (1.16)$$

where k is the Boltzmann constant. The mean kinetic energy obtained by integration over the distribution is $\langle \epsilon \rangle = kT$. The corresponding distribution of velocity v for a particle of mass m is given by:

$$f(v) = 4\pi \left(\frac{m}{2\pi kT} \right)^{\frac{3}{2}} v^2 \exp \left(\frac{-mv^2}{2kT} \right) \quad (1.17)$$

Therefore, the mean velocity is:

$$\langle v \rangle = \int_0^{+\infty} f(v) dv = \sqrt{\frac{8kT}{\pi m}} \quad (1.18)$$

In standard conditions ($kT = 25$ meV) the mean thermal velocity is 10^7 cm/s for electrons and it is of the order of 10^4 cm/s for ions, because of their mass ratio.

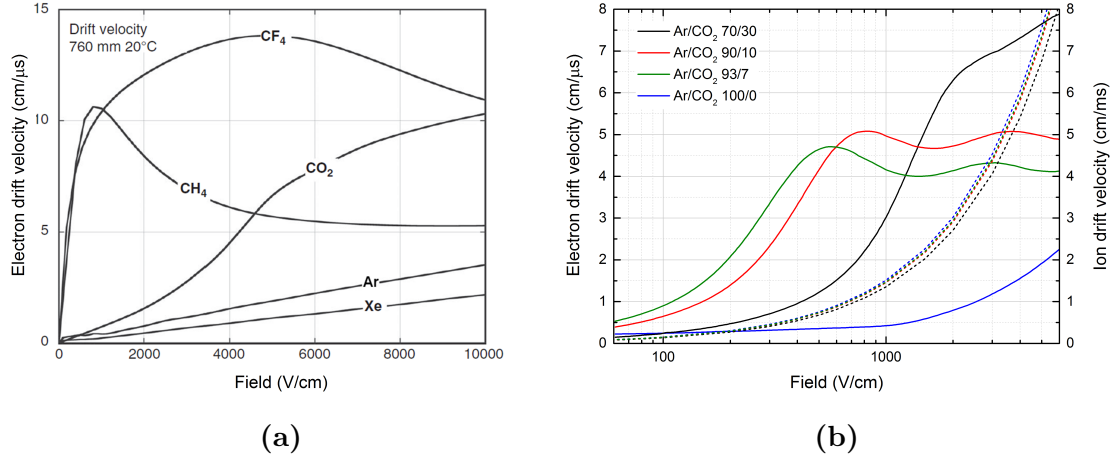


Figure 1.5: Computed electron drift velocity as a function of electric field at NTP for pure gases (left) [2] and for Ar/CO₂ mixtures (right) [3]. The dashed lines depict the ions velocities.

The position of a particle moving from the origin at time $t=0$ is Gaussian distributed; the following formula gives the fraction of particles in the element dx at a distance x from the origin and after a time t :

$$\frac{dN}{N}(x, t) = \frac{1}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right) dx \quad (1.19)$$

In the case of a one-dimensional diffusion process, the variance of the distribution is $\sigma_x^2 = 2Dt$, where D is called the *diffusion coefficient*.

In the presence of an external electric (drift) field E_d , charged particles move following the field lines. The average velocity of electrons or ions under the influence of the drift field is named the *drift velocity* (v_d), while the *mobility* μ is defined as v_d/E_d ; μ depends on the gas mixture and can be adapted to different pressure and temperature values using the formula:

$$\mu(P, T) = \frac{P_0}{P} \frac{T}{T_0} \mu(P_0, T_0) \quad (1.20)$$

For ions, the drift velocity turns out to increase linearly with the field magnitude, so that for a given gas mixture the mobility is constant. The energy acquired by ions between successive interactions is rapidly transferred to the gas atoms or molecules, so that their average energy remains almost unmodified. From the

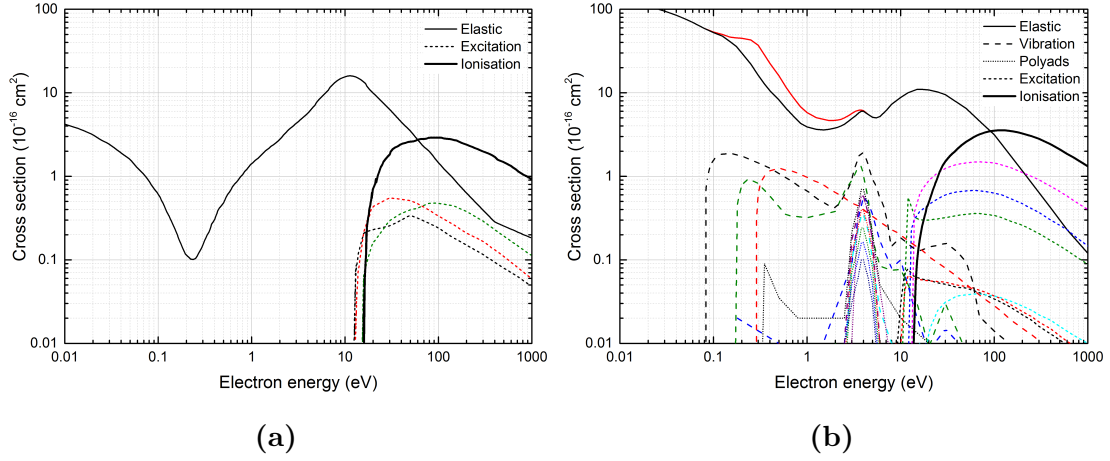


Figure 1.6: Electron cross section for Argon (left) and Carbon Dioxide (right).

Einstein formula

$$\frac{D_{\text{ion}}}{\mu_{\text{ion}}} = \frac{kT}{e} \quad (1.21)$$

one obtains that the standard deviation of the gaussian distribution (1.19) does not depend on the gas mixture:

$$\sigma_{x,\text{ion}} = \sqrt{2Dt} = \sqrt{\frac{2kTx}{eE_d}} \quad (1.22)$$

For electrons, mobility is strongly dependent on the electric field. In fact, due to their small mass, electrons can significantly increase their velocity between successive interactions, depending on the field magnitude. The following formula (Townsend, 1947) gives an expression for the electron drift velocity:

$$v_{d,e^-} = \frac{keE_d\tau}{m} \quad (1.23)$$

where τ is the mean time interval between successive interactions, k is the Boltzmann constant, m is the electron mass. Figure 1.5 shows the electron drift velocity as a function of the electric field magnitude for different gases. The dependence of v_d on the gas mixture is due to the different interaction mechanisms involved. As shown in Figure 1.6a, electrons moving in Ar can be scattered elastically or cause excitation or ionization. It is noticeable that the elastic scattering cross section has a minimum at $E = 0.5 \text{ eV}$ (*Ramsauer minimum*) and it increases significantly with the electron energy. At $E = 10 \text{ eV}$ elastic collisions are dominant

and the electrons are thermalized before reaching the ionization threshold energy. One way to reduce the elastic scattering probability is to add a polyatomic gas to the mixture. Indeed, while noble gas atoms de-excite through photon emission, polyatomic molecules have rotational and vibrational transitions without radiative emissions. Figure 1.6b reports the scattering cross section for electrons in CO_2 and shows the different inelastic contributions to the total cross section: addition of polyatomic gases to the mixture allows the dissipation of a large fraction of the electron energy without the production of photons. As the average electron energy is decreased, the total cross section approaches the Ramsauer minimum, so that the mean free path of electrons in the gas mixture is increased with respect to pure noble gases. At higher fields, the electron drift velocity in the gas increases and the probability of ionizing collisions exceeds the probability of excitations.

1.2.3 Charge amplification

Primary electrons accelerated by an intense electric field can reach sufficient energy to further ionize, producing secondary electron-ion pairs. Successively, both the primary and the secondary electron can acquire enough energy to ionize other gas molecules. This process leads to an exponential growth of free charges in the gas, that is called *avalanche*. The number of ionizations produced by an electron per unit length is named the *first Townsend coefficient* α and it is given by

$$\alpha = \lambda^{-1} = N\sigma_{\text{ion}} \quad (1.24)$$

where λ is the mean free path for ionization, i.e. the average distance between successive ionizations, N is the number density of gas atoms/molecules and σ_{ion} is the ionization cross-section for electrons in the given gas mixture. The first Townsend coefficient linearly depends on the gas density (and pressure) and it is a function of the electric field magnitude E . This dependency can be expressed through the *Townsend approximation* for the Townsend reduced coefficient:

$$\frac{\alpha}{P} = A \cdot e^{-B\frac{P}{E}} \quad (1.25)$$

where A and B are phenomenological constants. Since α indicates the number of ionization events per unit length, the number of electrons produced after a path dx

is $dn = \alpha n dx$, where n is the number of electrons in the position x . By integrating over a path x , one obtains the multiplication factor (or gain) G :

$$G = \frac{n}{n_0} = \exp \left[\int_{x_1}^{x_2} \alpha(x) dx \right] \quad (1.26)$$

In the case of a uniform electric field, α does not depend on the position and the multiplication factor increases exponentially with the electric field magnitude E . At high E and G , the avalanche growth creates a space charge distribution that modifies the electric field lines. This effect limits the multiplication factor at the upper value $G \simeq 10^8$, that corresponds to $\alpha x \sim 20$ (*Raether limit*).

In noble gases, the number of excited states increases with the electric field and only radiative de-excitation processes ($A^* \rightarrow A + \gamma$) can take place. In the case of a pure noble gas, the produced UV photons can not cause ionization; on the other hand, their energy (~ 10 eV in Ar) is higher than the work function of metals typically used in gaseous detectors (i.e. Cu). This leads to the extraction of a photo-electron from a metallic electrode that can cause a secondary avalanche. Since the photons produced by de-excitation can travel in the gas unhindered by the electric field, these secondary avalanches can occur in unrelated position and time with respect to the initial avalanche. The *second Townsend coefficient* β is defined as the mean probability for a secondary avalanche to occur per electron in the initial avalanche.

In order to reduce β , a polyatomic gas is usually added to the gas mixture. As previously discussed, small quantities of molecular gases (such as CO_2) influence the mean free path and the drift velocity of electrons in the gas. Furthermore, these gases can be excited by the UV photons and can de-excite through non-radiative processes such as rotational and vibrational transfers, so that they work as *quenchers*. If the excitation potential of the additional gas is lower than the excitation potential of the noble gas, a collisional charge transfer can take place ($A^* + B \rightarrow A + B^+ + e^-$, *Penning transfer*). The Penning transfer can occur if the lifetime of the excited state A^* is sufficiently long to cause the transfer before radiative de-excitation. This process effectively increases the ionization yield and contributes to the total gain.

Finally, the presence of electro-negative elements in the gas leads to electron capture events and to the formation of negative ions which drift towards the anode

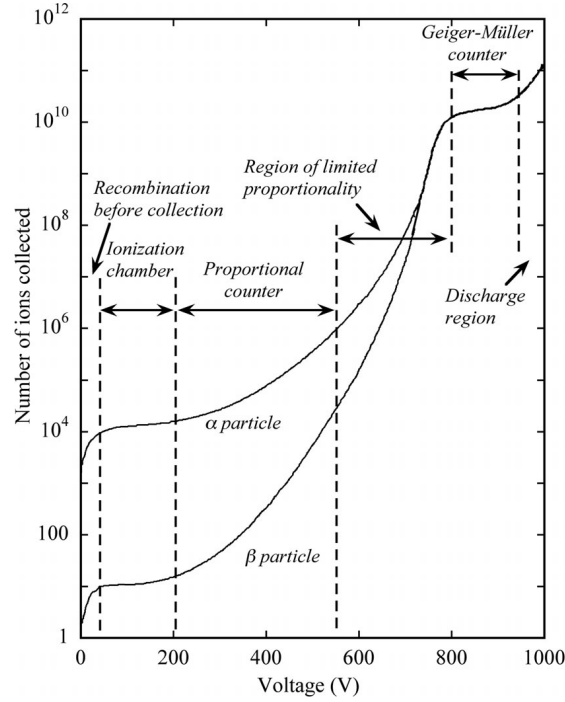


Figure 1.7: Charge collection in a wire chamber as a function of the applied voltage [2]. The different regions indicate the working regimes in which gaseous detectors can operate.

without contributing to the charge multiplication. Electro-negative elements such as oxygen O_2 and water H_2O are typically present as contaminants in detectors, while electro-negative gas mixtures are used to reduce the total charge produced in the avalanches in RPC detectors.

Depending on the electric field magnitude, different working regimes of gaseous detectors can be distinguished. Figure 1.7 shows the ions collected on the cathode of a wire chamber as a function on the applied voltage and indicates different operation modes. The following description can be adapted to all kinds of gaseous detectors.

- I. *Recombination* ($G < 1$): if the drift field magnitude is too low, the electron-ion pairs recombine before being collected.
- II. *Ion-chamber region* ($G = 1$): the entire ionization charge is collected at the electrodes.
- III. *Proportional chamber region* ($G \simeq 10^3 - 10^5$): each electron triggers a Townsend

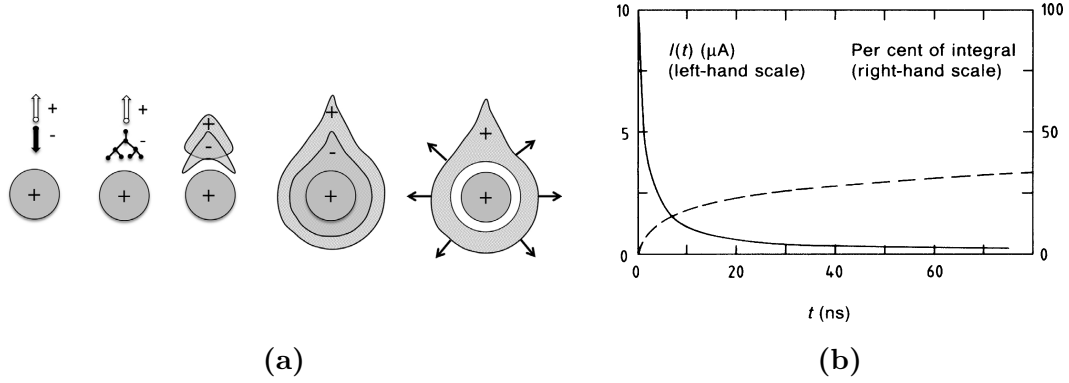


Figure 1.8: Development of a charge avalanche near the wire of a drift chamber (left) and induced current calculated using the Ramo-Schockley theorem (right).

avalanche of stable mean gain. The integrated charge is proportional to the number of primary ionizations, thus it is possible to measure the energy deposited by the ionizing particle.

- IV. *Limited proportionality* ($G \simeq 10^5 - 10^8$): at high gain, the space charge modifies the electric field and the proportionality between the signal and the primary ionization is gradually lost.
- V. *Geiger region* ($G \simeq 10^8 - 10^9$): the space charge effect becomes dominant and the avalanche reaches the Raether limit, thus the signal amplitude saturates. UV photons produced by electron-ion recombinations trigger secondary avalanches that are delayed and displaced with respect to the primary.
- VI. *Continuous discharge* ($G > 10^9$): the photon-triggered secondary avalanches create a conductive channel between anode and cathode and cause discharges.

1.2.4 Signal generation

The charges created in the gas volume of a gaseous detector move towards the electrodes, inducing electrical signals that can be read out by amplifiers. While electrons typically reach the anode within a time less than 1 ns, ions move towards the cathode with a velocity $\sim 10^3$ smaller, producing slow signals whose tail has a duration of hundreds of microseconds. Figure 1.8 shows the development of the electron-ion avalanche near the wire of a drift chamber and the current signal induced on the anode.

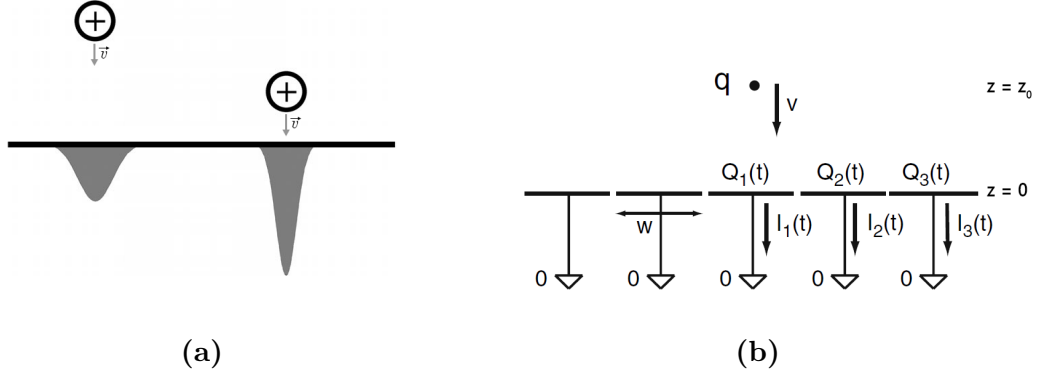


Figure 1.9: Sketch of signals induced on a plane electrode by a moving charge (left) and schematic view of a point charge moving towards a segmented electrode (right).

It is possible to calculate the charge induced on an infinite plane metal electrode by a charge q moving in a homogeneous electric field as illustrated in Figure 1.9. Solving the Poisson equation for the potential ϕ of a point charge q in the position z_0 , with the boundary condition $\phi(0) = 0$ on the electrode, and using the Gauss theorem to relate the electric field E to the charge surface distribution σ , one obtains:

$$E_z(x, y) = -\frac{qz_0}{2\pi\epsilon_0(x^2 + y^2 + z_0^2)^{\frac{3}{2}}} \quad E_x = E_y = 0 \quad (1.27)$$

where the solution can be calculated by assuming a mirror charge $-q$ in the position $-z_0$. The surface charge density is $\sigma(x, y) = \epsilon_0 E_z(x, y)$ and the total induced charge $Q = -q$ is obtained by integrating over the entire surface. If the metal plane is then segmented into strips of width w , considering the central strip and integrating the surface charge density over the strip area, it is possible to calculate the charge induced on the central strip:

$$Q_1 = \int_{-\infty}^{+\infty} \int_{-w/2}^{+w/2} \sigma(x, y) dx dy = -\frac{2q}{\pi} \arctan\left(\frac{w}{2z_0}\right) \quad (1.28)$$

It is noticeable that Q_1 depends on the position of the charge. If the charge is moving towards the electrode with velocity v , the induced charge is time-dependent and the induced current is:

$$I_1^{\text{Ind}}(t) = -\frac{d}{dt} Q_1(z_0(t)) = \frac{4qw}{\pi[4z_0(t)^2 + w^2]^2} v \quad (1.29)$$

It is important to underline that the current is induced by the movement of the charge: the electric signal is generated when the charge starts moving and drops to zero once the charge has reached the electrode.

The given example can be generalized to a system of N conductors connected to amplifiers or interconnected by a general network. The calculation of the induced signals is based on the Ramo-Schockley theorem [6, 7], which states:

The current induced on a grounded electrode by a point charge q moving along a trajectory $x(t)$ is

$$I_n^{\text{Ind}}(t) = -\frac{q}{V_w} E_n[x(t)]v(t) \quad (1.30)$$

where $E_n[x(t)]$ is the electric field defined by removing the charge q , setting electrode n to voltage V_w and grounding all the other electrodes. $E_n[x(t)]$ is called *weighting field of electrode n* .

The sign of the induced current depends on the sign of the moving charge and on the orientation of its velocity with respect to the weighting field of the electrode. In practical applications, the trajectories $x(t)$ must be computed considering the electric field geometry in the real detector and simulating the interaction between the particle (electron or ion) and the gas atoms or molecules, in order to obtain realistic drift velocities. For these purposes, software like COMSOL Multiphysics [9] and GARFIELD [10] are used. Further details on the calculation of induced signals in detectors can be found in Riegler (2008 [8]).

1.3 History of Micro-Pattern Gaseous Detectors

The history of gaseous detectors started with the development of the Single-Wire Proportional Counter by E. Rutherford and H. Geiger [11] for natural radioactivity measurements. The device, which is schematically shown in Figure 1.10, consists of a thin metal wire (the anode) coaxial with a cylindrical cathode and insulated from it. The cylinder is enclosed in a gas-tight volume and the application of a potential difference between the electrodes creates a radial electric field. The Single-Wire Counter evolved in '40s to the proportional counter, used to measure

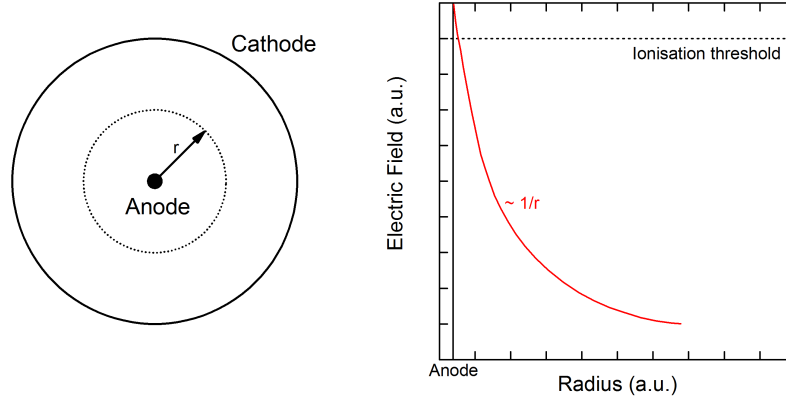


Figure 1.10: Schematic view of a SWPC (left) and dependence of the electric field on the distance from the wire (right). [3]

the energy deposit of the ionizing particle [12]. When a charged particle deposits its energy in the gas volume in form of primary ionization, the produced electron-ion pairs separate and move under the effect of the electric fields. Near the anode wire the electric field magnitude increases and the electrons multiply in a Townsend avalanche. While the avalanche electrons are almost instantaneously neutralized at the anode wire, the remaining ions drift towards the cathode tube, inducing a signal on the wire (Figure 1.8). One of the main limits of SWPCs is in their localization capability, since it is determined by the physical size of the detector.

In order to overcome the localization problem, in the late 1960s G. Charpalk developed the Multi-Wire Proportional Chamber (MWPC) [13] (Nobel prize, 1992). The MWPC detector consists of a set of parallel anode wires, symmetrically placed between two cathode planes. Thanks to this geometry, when a ionizing particle crosses the gas volume and an avalanche is produced near one of the anode wires, the negative signals induced on the capacitively coupled neighbour wires are compensated by positive signals induced by moving ions on all the electrodes. Thus, in MWPCs the wires work as independent proportional counters. A schematic view of the detector and the electric field lines are shown in Figure 1.11. The spatial resolution is determined by the anode wire distance, which has a lower limit ~ 2 mm for mechanical reasons. The main limit of MWPCs is given by the dependency of the gain upon the incoming particle flux [14]. Because of space charge effects,

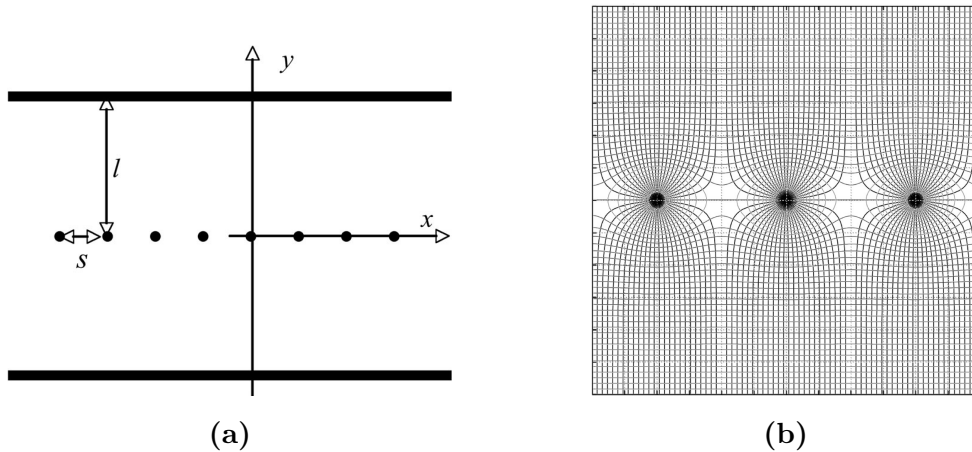


Figure 1.11: Schematic view of a MWPC (left) and electric field lines and equipotentials near the anode wires (right).

as the rate increases, the distortion of the electric field lines limits the gain, which is found to drop above a radiation flux of $\sim 10^4$ Hz/mm².

In the late 1980s the increasingly demanding requirements of particle physics experiments have led to the development of the Micro-Strip Gas Counter (MSGC) [15]. The fundamental idea behind MSGCs is to replace the wires of gaseous detectors with strips. The detector consists in an insulating plane where parallel metallic strips, alternately narrow and wide, are placed using photo-lithographic techniques. The narrow strips work as anodes and the wide strips as cathodes, and a parallel plane defines the drift gap. The electrons produced by an ionizing particle in the gas, drift towards the strips and are multiplied by the intense electric field (shown in Figure 1.12b). Signals are induced on the strips and on a segmented backplane in order to have a two-dimensional readout. The use of photo-lithographic technology makes it possible to place the strips at a distance (pitch) of about $200\mu\text{m}$ each other, considerably improving the spatial resolution. The use of supports with controlled resistivity improves the rate capability of MSGCs, whose gain turns out to be unaffected up to a radiation flux of $\sim 10^6$ Hz/mm² [16]. The main limit of this detector is related to the small distance between the electrodes. A highly ionizing particle, in a high rate environment, can trigger a discharge and permanently damage the detector. Moreover, MSGCs are sensitive to gas polymerization and pollution and they are subject to ageing

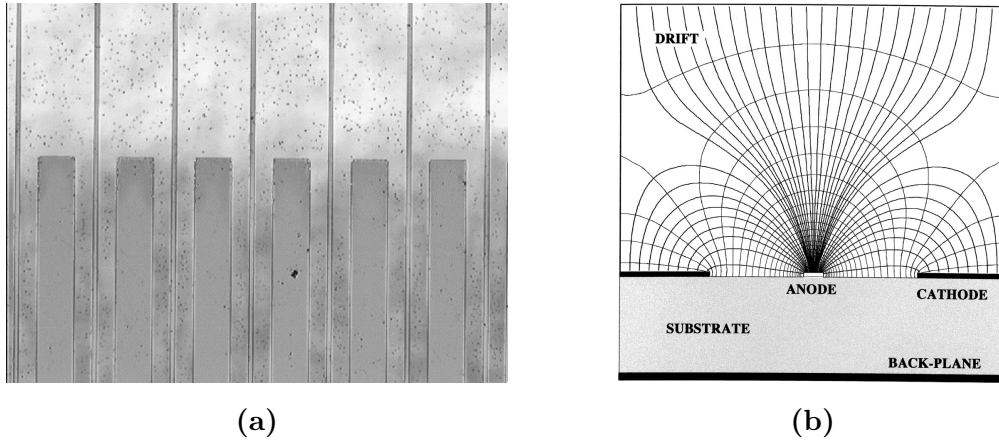


Figure 1.12: Close view of a MSGC plane (left) and electric field lines near the strips (right). [2]

effects [16].

Micro Pattern Gaseous Detectors (MPGDs) have been developed in the 1990s, in the continuity of the Micro-Strip Gas Counters. The name MPGD refers to a large number of detectors sharing patterned amplification structures and sub-millimetric sizes; they are summarized in [17]. The most common MPGDs are the MICRO-MESH Gaseous Structure (Micromegas) [18] and the Gas Electron Multiplier (GEM) [19] detectors.

1.3.1 Gaseous Electron Multiplier (GEM)

The amplification stage of a GEM detector consists of a thin polymer foil, metal coated on both sides and perforated. The holes have a uniform diameter and a high-density pattern (typically 50-100 holes/mm). The foil is placed between two parallel electrodes as illustrated in Figure 1.13a and the gas volume is splitted into a *drift* gap and an *induction* gap. With the application of appropriate potentials on the drift (cathode) and on the induction (anode) electrodes, the electric field lines follow the geometry shown in Figure 1.13b. A large potential difference is applied between the two sides of the foil and creates a high electric field inside the holes. The primary ionization charges released in the drift gap move towards the GEM foil and trigger Townsend avalanches that develop in the holes. A large

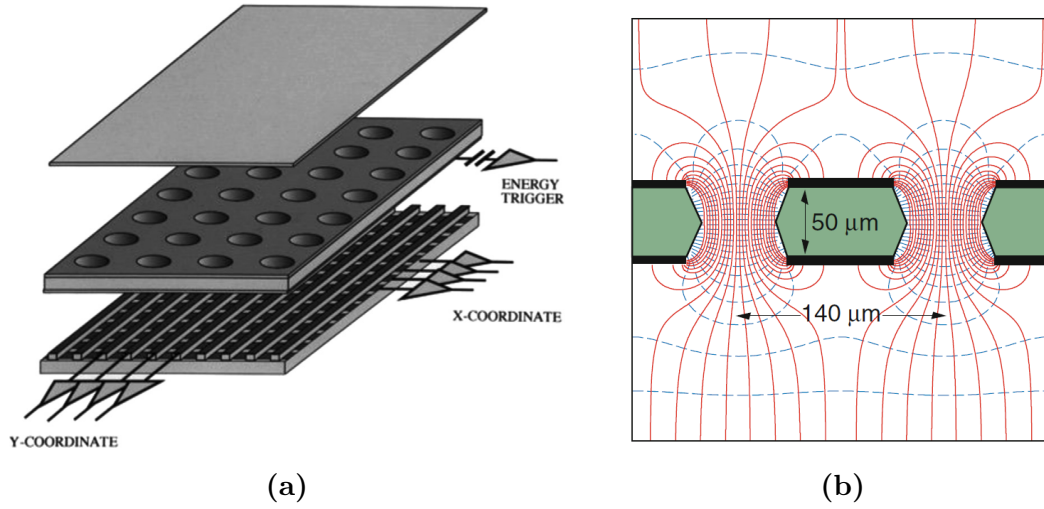


Figure 1.13: Schematic view of a single-GEM detector (left) [20] and electric field lines inside the holes in typical operating conditions (right) [21].

fraction of the secondary electrons drift towards the anode, inducing signals on a readout plane.

The multiplication factor depends on the diameter, shape and pitch of the holes, which varies with the chemical etching technique used. A *standard* GEM foil is usually defined as a $50\ \mu\text{m}$ -thick KaptonTM foil, coated with a $5\ \mu\text{m}$ -thick layer of Cu on both sides, with biconical holes (inner diameter $50\ \mu\text{m}$, outer diameter $70\ \mu\text{m}$, pitch $140\ \mu\text{m}$, see Figure 1.14). Moreover, the gain reachable using a single GEM foil depends on the quality of the production, since defects can locally modify the electric field lines and cause discharges. For this reason it is more feasible to obtain high gain values ($> 10^3$) with small detectors operated at high electric fields. In order to achieve a high multiplication factor in large area GEM detectors and operate in safe conditions, the multi-GEM structure is adopted.

Indeed, a specific aspect of GEM technology is the possibility to place multiple amplification stages in order to obtain a cascade multiplication of charges. The overall gain of a multi-GEM structure is the product of the single-GEM multiplication factors. A widely used multi-GEM detector is the triple-GEM, schematically illustrated in Figure 1.15, in which the gas gap between successive GEM foils is named *transfer* gap. The geometry of triple-GEM detectors has been optimized to

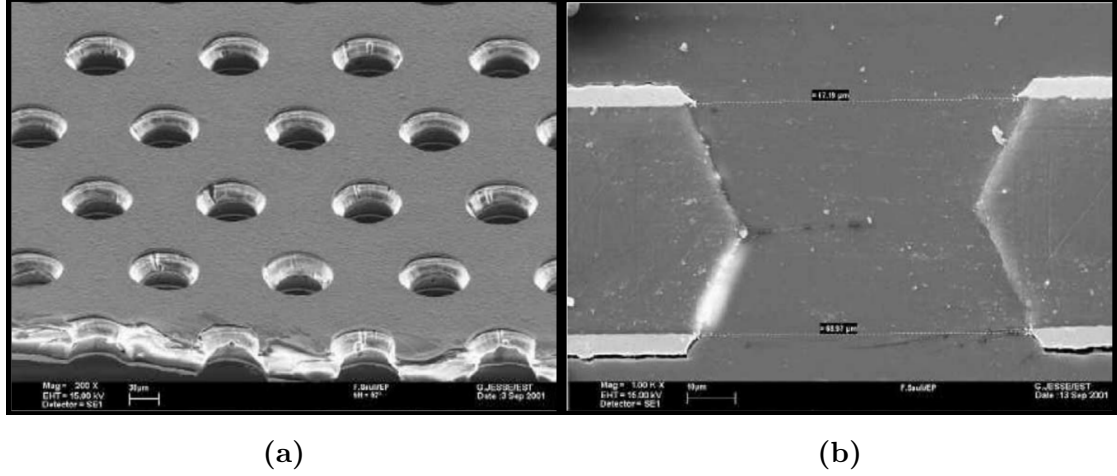


Figure 1.14: Electron microscope picture of a typical GEM foil (left) and cross-section through one single hole (right) [21].

obtain a high rate capability [25] and the configuration used in some LHC experiments, such as LHCb and CMS, consists in a 3 mm drift, 1 mm first transfer, 2 mm second transfer, 1 mm induction gap. Figure 1.16 reports the *effective* gain for a *standard* single-GEM detector, defined as the number of electrons reaching the anode per single primary electron. Therefore, the ratio between the effective gain and the real gain depends on the charge collection efficiency, which is related to the electric fields applied in the drift gap and in the induction gap. The optimization of GEM geometry and electric field values has been extensively studied with simulations [22] and measurements [23]. The influence of fields on the effective gain for a single-GEM detector will be discussed in Chapter 3.

GEM detectors were developed to achieve high rate capability and high accuracy localization of fast charged particles in High Energy Physics experiments, in order to overcome the MWPC limitations. As shown in Figure 1.17, the relative gain of a single-GEM detector remains unaffected up to a radiation flux of $\sim 10^6$ Hz/mm². Moreover, high spatial resolution have been achieved when using GEM-detectors as trackers, such as in the COMPASS experiment at CERN [24]. As an example, Figure 1.18 shows the distribution of residuals (i.e. the difference between predicted and measured coordinates) for an event detected by the COMPASS spectrometer. The width of the distribution (80 μ m) corresponds to the

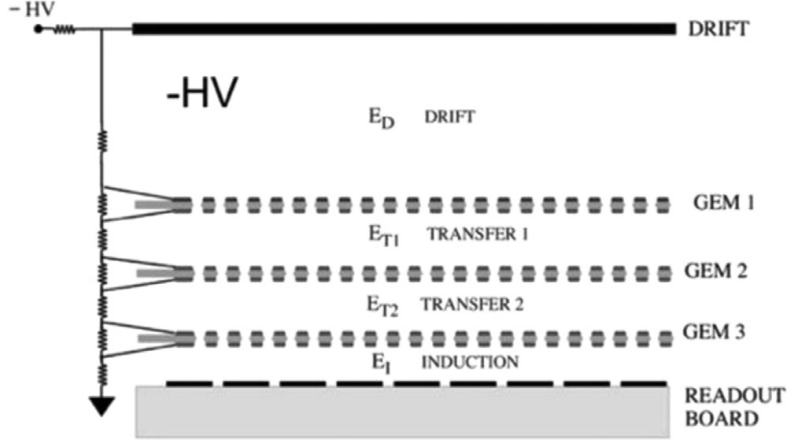


Figure 1.15: Schematic view of a triple-GEM detector [20].

position accuracy.

The typical time resolution of a LHC triple-GEM detector is of the order of 5 ns (Figure 1.19) and it is mainly due to the statistics of ion-pair production in the drift gap. As already mentioned, the cluster production along the path x in a gaseous detector is a Poisson point process: the probability that k clusters are produced along a certain path, given the average number of events per unit length, is Poisson-distributed (Eq. 1.13), while the distance between successive ionizations follows an exponential distribution (Eq. 1.14). Therefore, the probability that the j^{th} cluster is produced within the normalized position $x \in [0; 1]$ is given by the Erlang distribution [26]:

$$A_j^n(x) = \frac{x^{j-1}}{(j-1)!} n^j e^{-nx} \quad (1.31)$$

where n is the average number of clusters. Therefore, the probability that the cluster produced closest to the GEM foil ($j=1$) is detected in the interval $[0; x]$ is exponentially-distributed, with probability density function:

$$A_1^n(x) = n e^{-nx} \quad (1.32)$$

If the produced electrons drift towards the anode with mean velocity v_d , Eq. 1.32 gives the probability density function as a function of the arrival time t :

$$A_1^{n_p}(t) = n_p d e^{-n_p v_d t} \quad (1.33)$$

where $n_p = n/d$ is the average number of primary clusters per unit length and d is the full thickness of the drift gap. The standard deviation of the distribution (1.33) is

$$\sigma_t = (n_p v_d)^{-1} \quad (1.34)$$

The fluctuations over the arrival time of the electrons produced closest to the amplification foil determine the statistical contribution to the time resolution of a gaseous detector. We call σ_t the *intrinsic* time resolution. It should be noted that σ_t is calculated assuming that the closest electron is always detected. In real detectors, the intrinsic time resolution represents a lower limit to the time resolution, which is also affected by gain fluctuations and collection efficiency. For a GEM detector operated with Ar/CO₂ 70/30 gas mixture, with a drift field of 3 kV/cm, $n_p = 31 \text{ cm}^{-1}$ and $v_d \simeq 7 \text{ cm}/\mu\text{s}$, the intrinsic time resolution is $\sigma_t = (217 \mu\text{m}^{-1})^{-1} \simeq 5 \text{ ns}$. The contribution to the time resolution of the gain fluctuation is governed by the gas time constant $(\alpha_{\text{eff}} v_d)^{-1}$, where α_{eff} is the *effective* Townsend coefficient. By comparison, with a strong amplification field ($50 \div 100 \text{ kV/cm}$), this contribution to the time resolution is typically of the order of tens of ps. Thus, the time resolution of a GEM detector is dominated by the pair production statistics.

The design of a new gaseous detector with good time resolution would exploit the high rate capability ($>50 \text{ MHz/cm}^2$), excellent spatial resolution (down to $50 \mu\text{m}$), flexible geometry and cost-effectiveness of Micro Pattern Gaseous Detectors. Improving the time resolution would be useful for HEP experiments at high luminosity accelerators (e.g. HL-LHC) as well as for medical imaging applications. A fast timing MPGD could in fact contribute to the design of affordable TOF-PET scanners with improved image contrast and shorter scanning times. A gaseous detector designed to overcome the time resolution limit of Micro Pattern Gaseous Detectors will be presented in the next chapter.

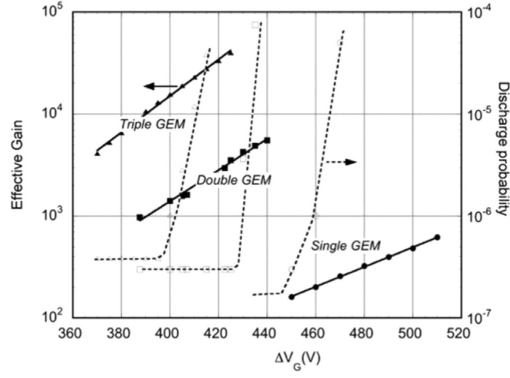


Figure 1.16: Effective gain (solid) and discharge probability (dashed) as a function of the voltage applied to each foil in multi-GEM detectors [20].

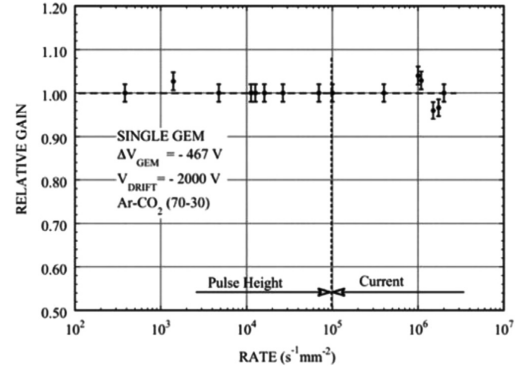


Figure 1.17: Relative gain as a function of rate for a single-GEM [20].

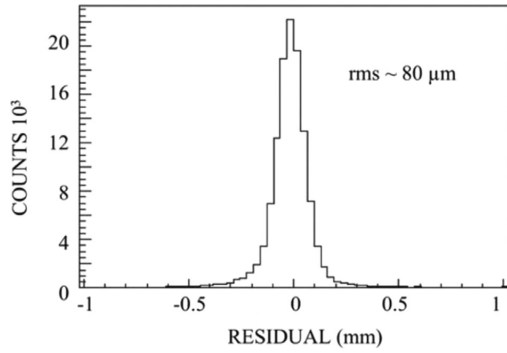


Figure 1.18: Distribution of the position accuracy for fast particles measured with triple-GEM tracking detectors in the COMPASS experiment. [24].

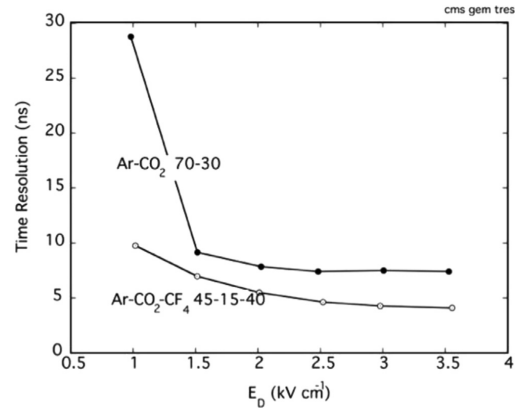


Figure 1.19: Time resolution (rms) for fast particles measured with Ar-CO₂ and Ar-CO₂-CF₄ gas mixtures as a function of drift field. [20].

Chapter 2

The Fast Timing MPGD (FTM)

The time resolution of a *standard* triple-GEM detector is determined by the statistical fluctuations on the position of the ion-pairs produced in the drift region and it is typically around $\sigma_t \simeq 5$ ns (see Figure 1.19). Moreover, due to the small distance between the anode and cathode electrodes, the single-GEM foil multiplication factor is limited to $\sim 10^3$ by the occurrence of discharges. For GEMs, the reduction of the discharge probability has been achieved sharing the gain among multiple amplification stages (like in triple-GEM detectors, see Figure 1.16). For Micromegas detectors [18], the spark occurrence between the amplification stage (a metallic mesh) and the readout plane (PCB with copper strips) has been reduced with the introduction of a resistive layer deposition on top of the readout [27]. This solution employs the same principle of auto-quenching used in Resistive Plate Chambers (RPCs) [28].

The Fast Timing Micro-pattern gaseous detector (FTM) has been designed by R. De Oliveira, M. Maggi and A. Sharma [29] to improve the time resolution in a robust and spark-protected MPGD.

2.1 Working principle

In MPGDs the drift and the amplification processes take place in separated zones of the detector. The time of detection of the ionizing particle is the arrival time of the closest electron at the end of the drift zone. We call d_{near} the distance

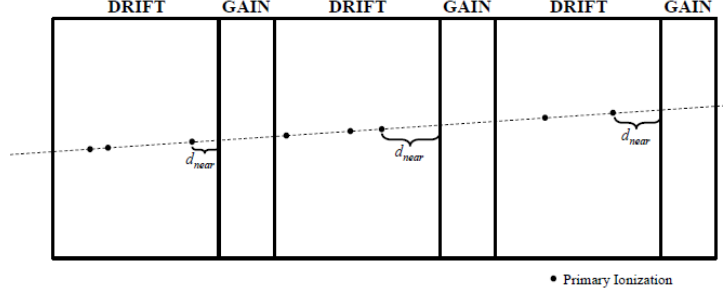


Figure 2.1: Schematic description of the FTM working principle: the segmentation of the drift gap reduces the fluctuation of the primary ion-pairs position. The detected arrival time is determined by the minimum d_{near} event.

between this cluster and the amplification layer. As discussed in Section 1.3.1, since d_{near} follows the exponential distribution (1.32), the contribution of the time arrival fluctuations to the time resolution is given by (1.34):

$$\sigma_t = (n_p v_d)^{-1} \quad (2.1)$$

where n_p is the average number of primary ionizations per unit length and v_d the drift velocity, which depend on the gas mixture and on the electric field.

The basic idea of the FTM design is the segmentation of the drift gap into thinner gaps, each with an independent amplification structure [29]. As shown in Figure 2.1, the arrival time of the ionizing particle is determined by the electron-ion pair produced at minimum distance from one of the amplification stages. If the drift gap is segmented into N evenly-spaced layers, with $X_i \in [0; 1]$ the stochastic variable that indicates the normalized distance between the last cluster produced in the i -th drift gap and the i -th amplification layer, the probability that the last cluster is produced within the distance x_i is given by Eq. 1.32:

$$P(X_i \leq x_i) = \int_0^{x_i} A_1^n(y) dy = 1 - e^{-n x_i} \quad (2.2)$$

where n is the average number of primary ionizations in the i -th drift gap. The minimum distance event is described by the variable $Z = \min_{i=1..N} \{X_i\} \in [0; 1]$, whose cumulative distribution function is:

$$B_1^n(z) = P(Z \leq z) = 1 - P(X_i > z \ \forall i = 1..N) = 1 - e^{-nz \cdot N} \quad (2.3)$$

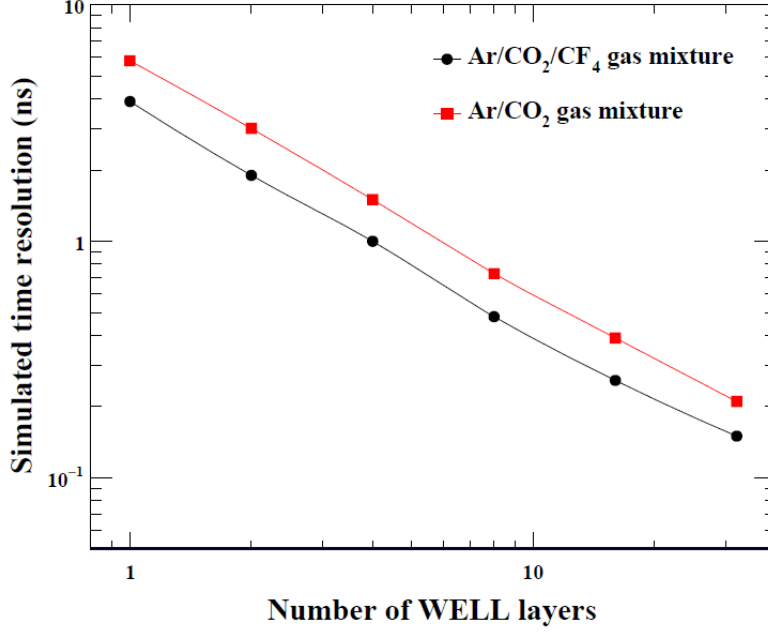


Figure 2.2: Simulated time resolution of the FTM device as a function of the number of WELL layers for two standard gas mixtures: Ar/CO₂ 70/30 (full squares) and Ar/CO₂/CF₄ 45/15/40 [29].

where the X_i are assumed to be independent variables. Thus the variable Z is exponentially distributed, with standard deviation:

$$\sigma_z = (n \cdot N)^{-1} \quad (2.4)$$

Substituting the normalized coordinate z with the arrival time $t = v_d z d$, where d is the drift gap thickness, one obtains the intrinsic time resolution for a segmented drift gap:

$$\sigma_t = (n_p v_d N)^{-1} \quad (2.5)$$

which is reduced by a factor N with respect to the situation with a single gap (2.1). This result is confirmed by the simulation of timing response shown in Figure 2.2, performed with GARFIELD [10].

As discussed in 1.2.1, the efficiency of an ideal gaseous detector depends on the number of primary pairs produced by the ionizing particle in the given gas mixture and on the gas volume thickness. Since a GEM detector with a 3 mm thick drift

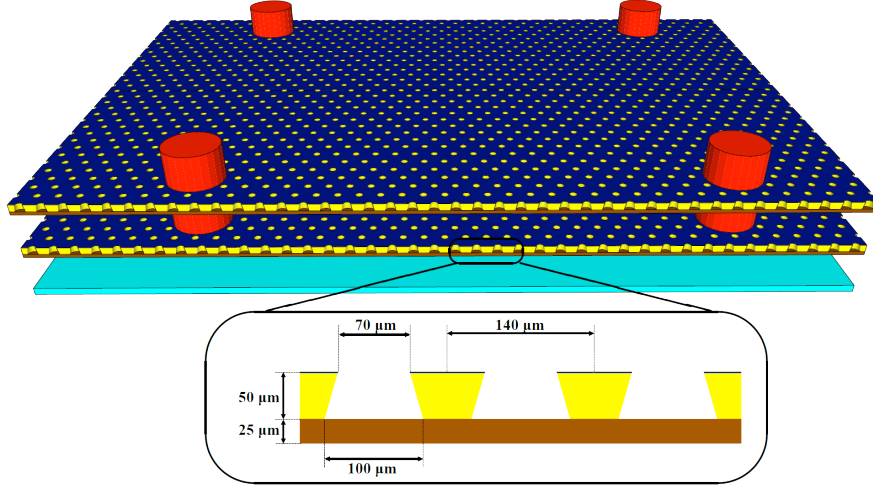


Figure 2.3: Drawing of the full resistive WELL layers used in the implementation of the FTM. The perforated foil (yellow) has a DLC coating on the top (dark blue) and it is closed by an antistatic polyimide foil (brown). The red cylinders are the pillars. [29].

gas is fully efficient, the number of layers N in the FTM must compensate the inefficiency of the single thin-drift structure.

Each amplification stage consists of a fully resistive WELL foil, illustrated in Figure 2.3. The WELL detectors [30], introduced in 1998, are position-sensitive gaseous proportional detectors based on a kapton foil coated with gold-plated copper on both surfaces and perforated, similar to a GEM foil, but directly closed by a metallic readout plane. The main difference between GEM and WELL detectors is that the GEM foil does not provide spatial information on the avalanche, because the electrical signals need to be induced on a segmented readout plane placed at a certain distance from the amplification zone. In the WELL detectors, the readout strips are placed directly onto the kapton foil and each hole provides the position of the avalanche. Therefore, the resulting detector is resistant to the mechanical stress.

In the Resistive-WELL detectors (R-WELLS) [31, 32] (2015), a resistive layer ($R \sim 10 \div 10^3 M\Omega/\square$) covers the readout plane in order to avoid sparks and achieve higher gain. The fully resistive WELLS used in the implementation of the FTM detector are similar to R-WELLS, with the difference that the copper electrodes are replaced by thin resistive coatings. The use of resistive materials reduces the

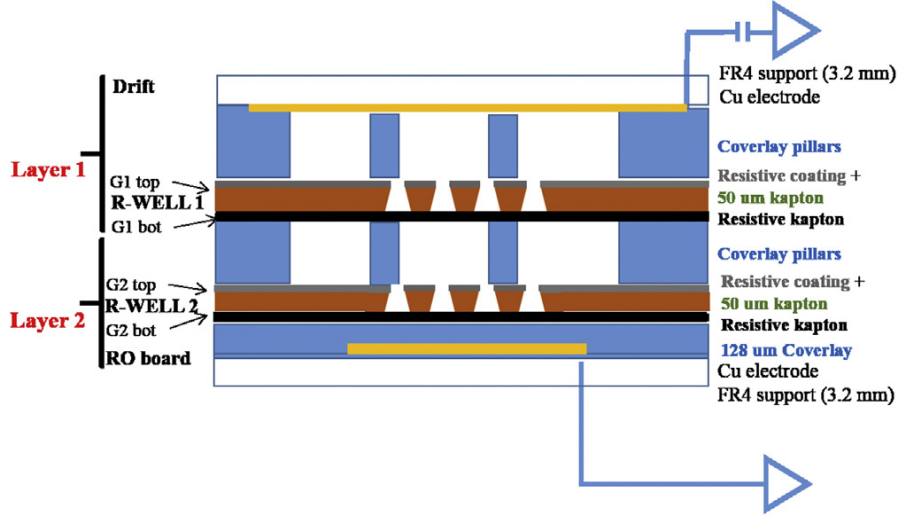


Figure 2.4: Schematic view of the first FTM prototype [34].

discharge probability at high gain [27]. Moreover, the FTM is conceived as a multi-layer detector which exploits the transparency of the overall resistive structure to transients [33], so that electrical signals are induced on readout planes placed on the top and on the bottom of the detector, even in the presence of powered resistive layers.

2.2 FTM prototypes

2.2.1 The first prototype

The first prototype of Fast Timing Micro-pattern gaseous detector was produced in 2015 [29, 34] and it is schematically shown in Figure 2.4. The structure of the detector was composed by two drift-amplification stages. Each amplification layer consisted of a $50 \mu\text{m}$ thick polyimide foil¹, which was coated with a DLC² sputtering technique in order to obtain a high surface resistivity (up to $\sim 10^3 M\Omega/\square$). The foil was perforated with inverted truncated-cone-shaped holes

¹Apical polyimide, produced by Kaneka Corp. [37]

²DLC is a class of amorphous carbon material that displays some of the typical properties of diamond [38]. DLC is widely used in the production of coatings and thin films because of its hardness, flexibility and low friction coefficient.

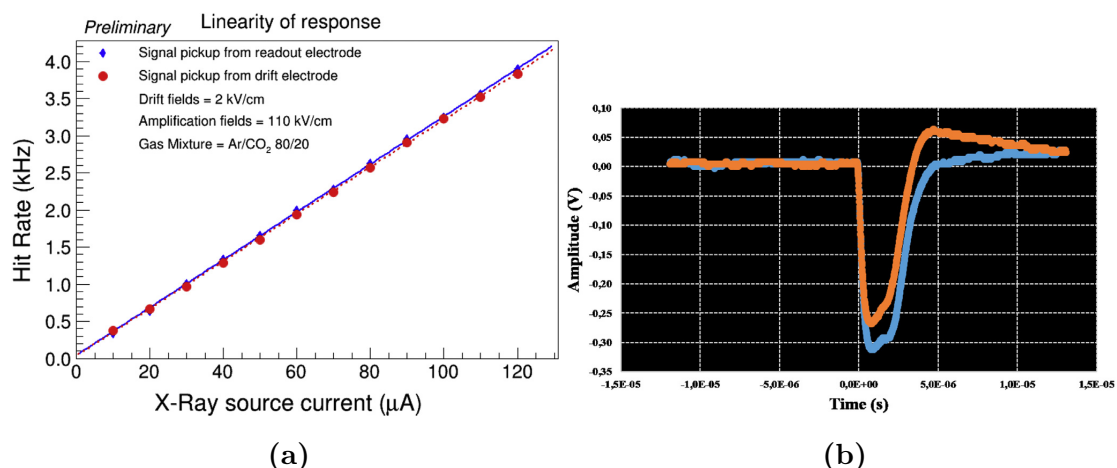


Figure 2.5: Results of the preliminary characterization of the first FTM prototype performed with X-rays [34]: measured hit rate from both top and bottom planes of the FTM as a function of the X-ray current (i.e. the incident flux) (left) and signals picked up from the readout (blue) and drift (orange, inverted) after amplification and shaping (right).

(bottom base diameter: $100\ \mu\text{m}$, top base diameter: $70\ \mu\text{m}$, pitch: $140\ \mu\text{m}$, see Figure 2.3) and it was stacked on a $25\ \mu\text{m}$ thick Kapton³ foil due to electrostatic force induced by polarisation. The planarity of the structure was ensured by $250\ \mu\text{m}$ high coverlay pillars, which defined the drift gap thickness. The two amplification-drift stages could be polarized independently and the signals were induced on readout planes placed on top and bottom of the detector. The active area was about $20\ \text{cm}^2$ and the structure was glued to guarantee the stretching of the foils.

Several tests on the first FTM prototype were performed at CERN during 2015 and the results are reported in [34] and [35]. Preliminary measurements with X-ray photons proved the linearity of the response to the radiation rate (Figure 2.5a) and the electrical transparency of the resistive structure (Figure 2.5b). In order to measure the time resolution of the detector, a two-week test beam was carried out at the SPS H4 beam line at CERN, with muon and pion beams. From Equation 2.5, using Ar/CO₂ gas mixture, the time resolution of a two-stages FTM

³Resistive polyimide film developed by DuPont [39].

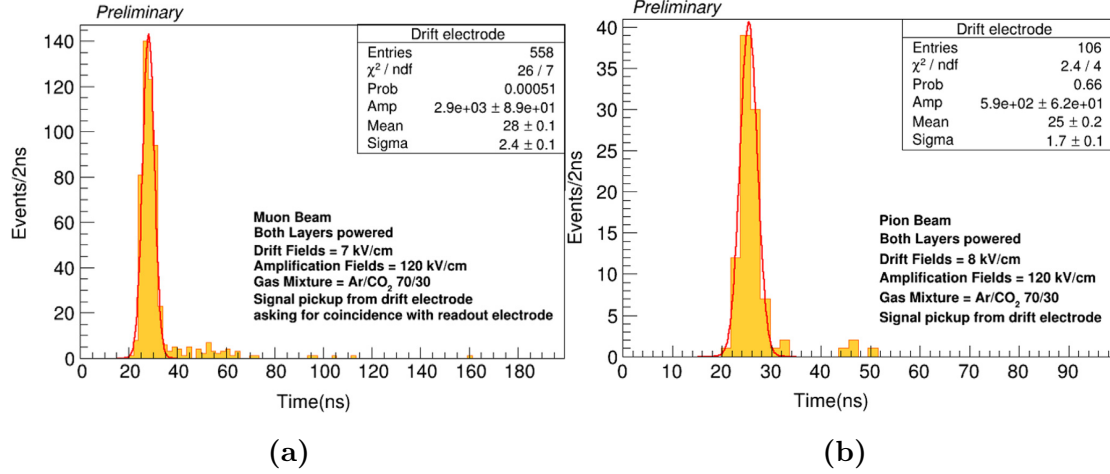


Figure 2.6: Time distribution of the events induced by muons (left) and pions (right) in the FTM detector. The time resolution is evaluated as the sigma of the gaussian fit [34].

is expected to be around 2 ns. As reported in Figure 2.6, the measured time resolution was $\sigma_t = (2.4 \pm 0.1)$ ns with muon beam and $\sigma_t = (1.7 \pm 0.1)$ ns with pion beam.

Because of the small number of drift gaps and of their thickness ($2 \times 250 \mu\text{m}$), the efficiency of the first FTM prototype was limited by primary ionization statistics and it was expected to be up to $\sim 80\%$. Preliminary tests with cosmic rays revealed that the efficiency of the prototype was even lower than expected ($\sim 20\%$) and this result suggested that the amplification foils were working at low gain, while the readout electronics used to amplify and shape the FTM signals, which was designed for larger triple-GEM signals, was not efficient for small and fast signals [35].

Because of the small ionization charge produced in the $2 \times 250 \mu\text{m}$ -thick drift gap, in the absense of a dedicated electronics it was not possible to measure the effective gain of the first FTM prototype, which is the ratio between the charge collected at the anode and the ionization charge [35]. Thus, the main limitations of the first FTM prototype were the small size of the induced signals and the low efficiency. The way to improve the efficiency is increasing N, but the first prototype was glued and it was not possible to add extra layers. Moreover, the acquisition

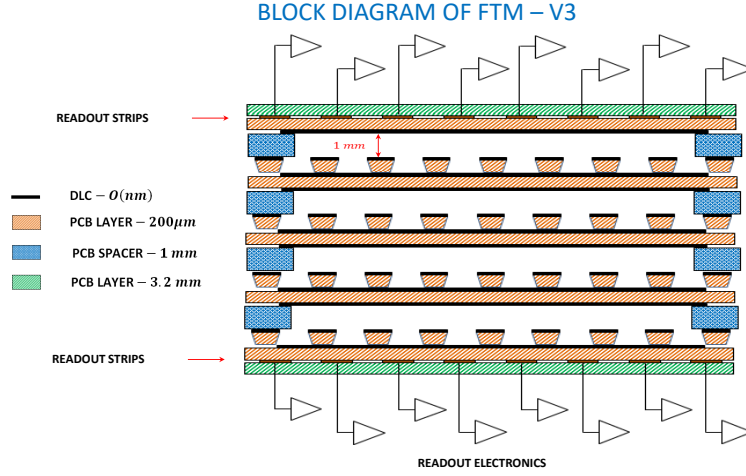


Figure 2.7: Schematic view of the FTM v.3 prototype with thick-PCB amplification foils.

of fast and small signals required a dedicated electronics.

2.2.2 The Micromegas based prototype

A second version of the FTM was produced during 2015. The main difference with respect to the first prototype was in the amplification foil, which consisted of a resistive $125\ \mu m$ -thick mesh obtained drilling a Kapton foil. In order to overcome the limitations of the glued prototypes, which are fragile and not expandable, the FTM v.2 had a modular design. Thus, the preliminar version of the detector consisted of a single drift and amplification stage and it was planned to add 3 more stages. After some preliminary tests on the single-stage prototype, a 4-layers version was assembled but, due to signal induction problems, the modular design was abandoned.

2.2.3 The thick-GEM based prototypes

In order to overcome the limitations of the first prototype, two successive FTM devices have been produced in 2016. The FTM v.3 was a 4-layer prototype with 1 mm-thick drift gaps and it is shown in Figure 2.7. Each amplification stage con-

sisted of a 200 μm -thick PCB foil, similar to a thick-GEM foil [36]. The cylindrical holes were obtained with a standard drilling technique and had a diameter of 200 μm and a pitch of 500 μm . The PCB had a graphite printed screen on top, which provided a surface resistivity of $5 \div 10 \text{ M}\Omega/\square$. Each amplification foil was stacked on a PCB layer, 200 μm thick, covered by a graphite resistive layer on both top and bottom. The drift and the amplification foils were separated by a 1 mm-thick PCB mesh that worked as a spacer, with small grooves for the refreshing of the gas mixture. The active area was only 12 cm² (4 cm diameter) due to limitations in the drilling technique. The detector was designed to be completely modular: the bottom readout PCB could hold up to 12 layers, with independent high voltage connections. The readout plane consisted of 200 copper strips for X (top) and Y (bottom) spatial localization. The strips were connected to 4 panasonic connectors through long vias in the PCB.

The thick-GEM-like amplification structure was expected to provide a large gain and the 4-layer structure was designed to be fully efficient. During the preliminary tests, it was not possible to safely operate the detector at high voltage, because of discharges which occurred at $E_{\text{amp}} \simeq 50 \text{ kV/cm}$. The graphite resistive layers turned out to be damaged by the standard cleaning procedure that followed the drilling, so that the surface resistivity of the foils was not uniform. Moreover, since the PCB foils were not glued together, it is possible that the electric field fluctuations due to spatial charge effects affected the foils stretching and thus modified the distance between the electrodes.

A second version of the thick-FTM was assembled during 2016. The prototype consisted of a single amplification stage made of a 250 μm -thick polyimide foil, obtained gluing together two 125 μm -thick foils. The drift and amplification region were covered on both sides with resistive materials. The holes were created by mechanical perforation (diameter 200 μm , pitch 500 μm). The drift region was 4 mm-thick and the active area was approximately $2 \times 2 \text{ cm}^2$ large. The detector framework design, consisting of the top and bottom readout PCB layers and the gas cover, was the same used for the FTM v.3. A rigid PCB layer was added on top of the structure to push the foils together.

The FTM v.3b was affected by discharges like the previous prototype, maybe

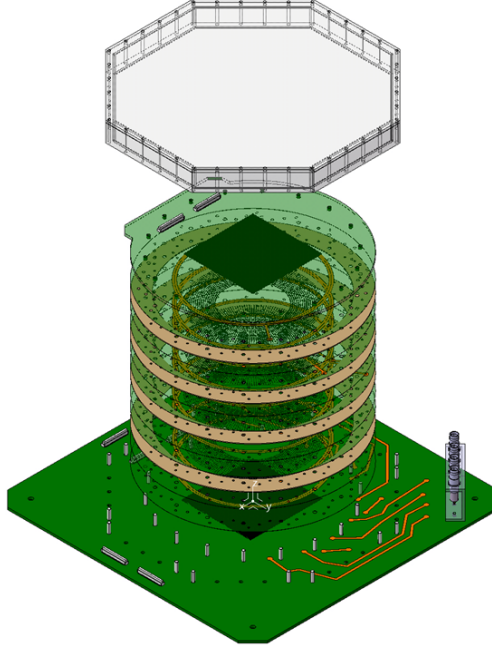


Figure 2.8: Modular design of the FTM prototype.

due to imperfections in the holes or in the resistive deposit. Furthermore, it is possible that the gas refreshing was not fast enough to eliminate the pollution from the active region. Finally, an electric problem was found in the PCB spacers, which probably modified the electric field lines in close proximity to the holes causing the discharges.

2.2.4 The new prototype

A new prototype of Fast Timing Micro-pattern gaseous detector has been produced in 2017 and is the prototype tested in this thesis. The basic idea of the FTM v.4 design is to go back to the $50\ \mu\text{m}$ -thick amplification foils used in the very first prototype, increasing to $N = 4$ the number of layers and exploiting, with some upgrades, the modular design used for the FTM v.3.

As shown in Figure 2.9, the new prototype consists of 4 independent drift-amplification stages simital to those used in the first prototype. The amplification structure is made of a $50\ \mu\text{m}$ thick Kapton foil previously coated in order to obtain a DLC/Polyimide/Cu FCCL layering. The amplification disks, obtained

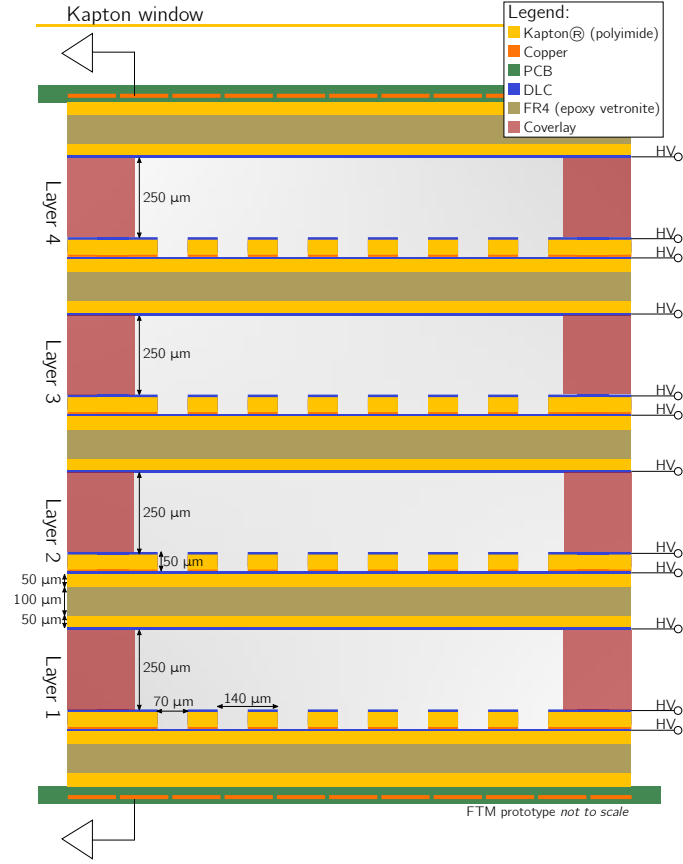


Figure 2.9: Schematic view of the new FTM prototype.

by etching, have biconical shape, with diameter $\sim 70 \mu m$ and pitch $140 \mu m$ (see Figures 2.11b and 2.11a) and the active area is of $\sim 20 \text{ cm}^2$, almost twice the FTM v.3 active area which was limited by the drilling technique.

Each amplification foil is stacked on an insulating plane, DLC coated on both sides, which is composed by two $50 \mu m$ -thick polymide layers reinforced by a $100 \mu m$ -thick FR4 layer in the middle. The drift gaps are $250 \mu m$ -thick and the planarity is ensured by a set of coverlay pillars placed on the bottom of each insulating plane (Figures 2.11c and 2.11d). Each DLC layer is encircled by copper tracks connected to external HV pins.

With the DLC sputtering technique it is possible to realize a DLC coating with surface resistivity in the range $[10; 1000 \text{ M}\Omega/\square]$ at will. The DLC coatings used for this prototype have a surface resistivity of $30 \div 50 \text{ M}\Omega/\square$ before etching, while,

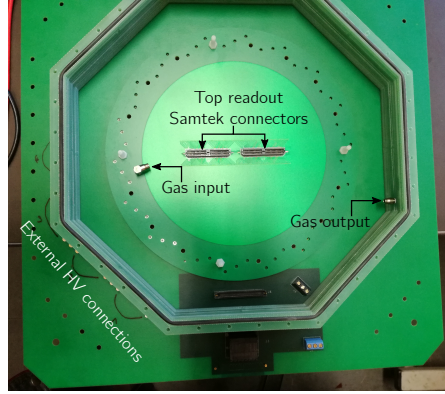


Figure 2.10: Picture of the prototype during the assembly.

after the etching, the resistivity is expected to increase by a factor of 10. During the assembly, the top surface resistivity of each amplification foil was measured using a Megger insulation tester and it was on average around $500M\Omega/\square$. The surface resistivity of the drift foils was measured on both sides and it was $\sim 50M\Omega/\square$. Detailed values are reported in Table 2.1.

The overall structure of the detector is closed between two PCB layers, each containing 200 X (top) and Y (bottom) readout strips directly connected to two *Samtec* connectors which replaced the *Panasonic* used in the FTM v.3 (Figure 2.10). The main difference between *Panasonic* and *Samtec* connectors is in the ground pin placement, the first having two ground pins placed at each end of the connector, the latter providing a unique rugged ground at the center of the connector. The prototype design, shown in Figure 2.8, is the same modular designed of FTM v.3 and it can host up to 8 additional drift-amplification layers. The main differences between the FTM v.3 and v.4 are in the optimisation of the signal path length, which is reduced by placing the readout connectors directly on top and bottom of the active area, in order to reach better signal-to-noise ratio in the acquisition of small signals. Moreover, the gas input has been placed on top of the PCB so that the gas is forced to flow through all the layers.

Table 2.1: Resistivity of the DLC layers for the FTM v.4 prototype, measured with Megger insulation tester. The layers are numbered as in Figure 2.9.

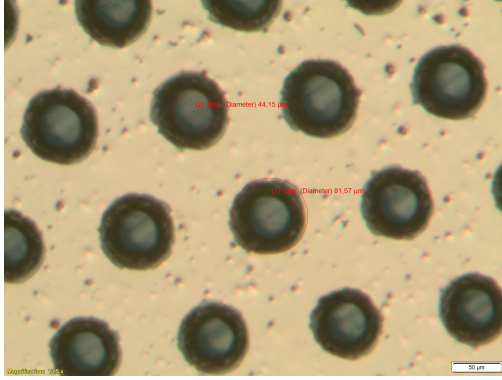
	Layer 1	Layer 2	Layer 3	Layer 4
Drift	30 M Ω	35 M Ω	40 M Ω	50 M Ω
Amp. top	360 M Ω	450 M Ω	1.1 G Ω	450 M Ω
Amp. bottom	40 M Ω	35 M Ω	37 M Ω	30 M Ω

2.3 Future perspectives

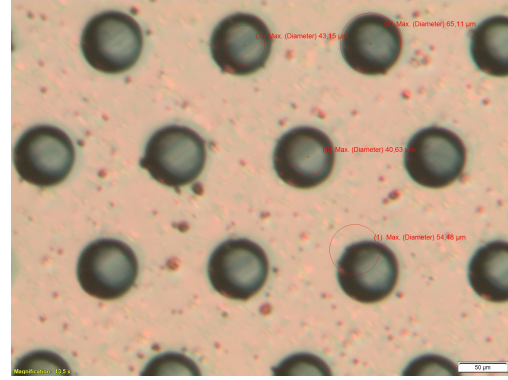
The FTM v.4 has been designed to confirm the results obtained with the first FTM prototype with a dedicated electronics. As will be discussed in Chapter 5, an optimized readout electronics is therefore necessary to acquire small signals (~ 1 fC) with high time resolution (~ 100 ps) like the ones produced by the FTM. Some preliminary tests performed on the FTM v.4 with x-rays in Ar/CO₂ 70/30 will be presented in Chapter 4, together with the limitations of the x-ray test setup. Some activities are planned for the FTM v.4:

- I. *Gas mixture optimisation*: using different gas mixtures (Ar/CO₂, Ar/CO₂/CF₄, Ar/iC₄H₁₀, Ne/iC₄H₁₀), higher gain can be achieved.
- II. *Laser test setup*: the use of X-rays to test the FTM prototypes is complicated because of the geometry and the materials used. For the future, the building of a test stand based on an Ultra Violet (UV) laser is planned [41].
- III. *Dedicated electronics*: the FATIC readout chip developed by INFN-CAD team in Bari needs to be configured for synchronous signal acquisition, in order to prepare a setup for efficiency measurement with fast scintillators.
- IV. *Test beam setup*: for tests with muon and pion beams at the SPS facility at CERN, the experimental setup with GEM trackers needs to be prepared.

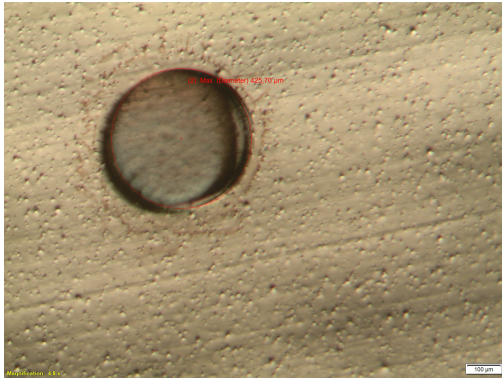
Finally, a N=12 layers prototype will be assembled, in order to reach the sub-nanosecond scale for the time resolution in a fully efficient device.



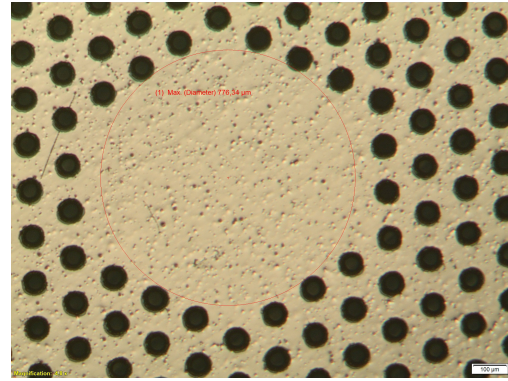
(a) Top side of the amplification foil, DLC coated.



(b) Bottom side of the amplification foil, Cu coated.



(c) Coverlay pillar placed on the DLC coating of the drift electrode.



(d) Detail of the amplification layer, showing a zone without holes to support the pillars.

Figure 2.11: Optical microscope pictures of the foils placed in the FTM prototype.

Chapter 3

Tests on the Single-GEM Detector

The FTM v.4 amplification foil has features similar to those of a *standard* GEM foil. Since most of the detector performance parameters, i.e. multiplication factor and rate capability, are strongly related to the foil geometry [23], the *standard* single-GEM detector has been used as a benchmark for further tests on the FTM prototype, with focus on the *effective* gain. Moreover, since the single-GEM detector exhibits a low gain ($\sim 10^3$), the optimization of an experimental setup for the acquisition of small signals turns out to be useful for the preliminary tests performed on the FTM prototype.

In this chapter the results of the tests performed on a single-GEM detector prototype are presented. The detector and the experimental setup are described in the first section, while in the second section the results are discussed.

3.1 Single-GEM prototype

The main goal of the tests was to measure the effective gain of the single-GEM detector, in order to better comprehend the limitations of a single $50\ \mu\text{m}$ -thick amplification structure and to have a reference for the FTM gain. Moreover, the $50\ \mu\text{m}$ single-GEM has been used as a benchmark by Bencivenni ([31] 2015) for the tests on the Micro-RWELL detector, whose amplification foil is similar to the

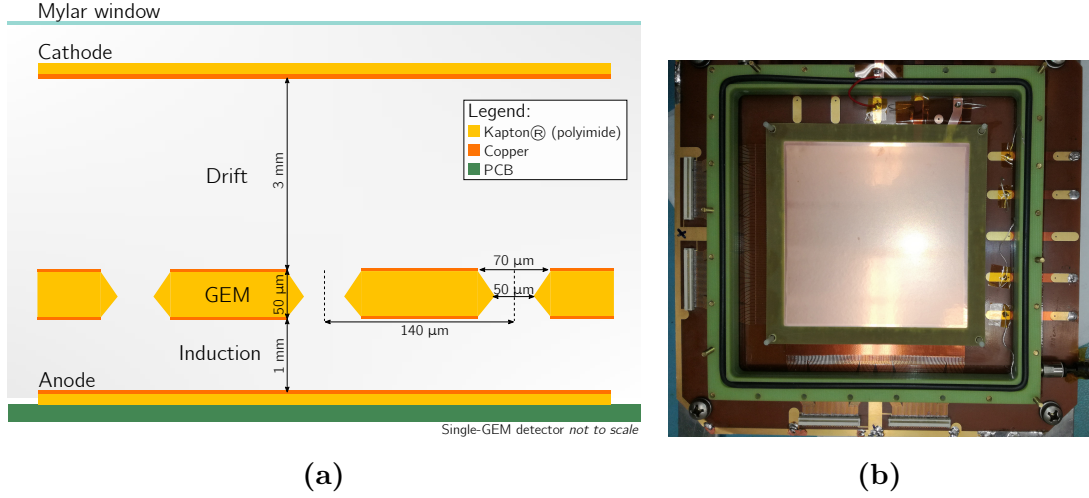


Figure 3.1: Schematic drawing of the single-GEM detector (left) and picture of the prototype.

ones used in the FTM v.4 prototype.

The single-GEM detector used is a $10 \times 10 \text{ cm}^2$ prototype and it is schematically shown in Figure 3.1a. The amplification foil is a standard $50 \text{ }\mu\text{m}$ -thick Kapton foil, copper coated on both sides. The holes, made by a double-mask etching technique, have biconical shape, inner diameter of $50 \text{ }\mu\text{m}$, outer diameter of $70 \text{ }\mu\text{m}$ and pitch of $140 \text{ }\mu\text{m}$.

Plastic spacers are used to set the distance between the electrodes. The drift and induction gap have standard thickness (about 3 mm and 1 mm respectively). The readout plane of the prototype originally consisted of a set of X-Y strips connected to 4 Panasonic connectors through long vias in the PCB (see Figure 3.1b). As explained below, the tests are performed powering all the planes of the detector. For this reason, the readout plane has been replaced with a unique copper pad.

The gas volume is confined by an epoxy frame containing two elastomer O-rings which ensure the gas tightness. On the top, the detector is closed by a PCB plane with a large Kapton window, which is transparent to soft X-rays.

In order to polarize the gas gaps, the four electrodes (here named cathode, top GEM, bottom GEM, anode) are connected to external copper vias placed in the PCB.

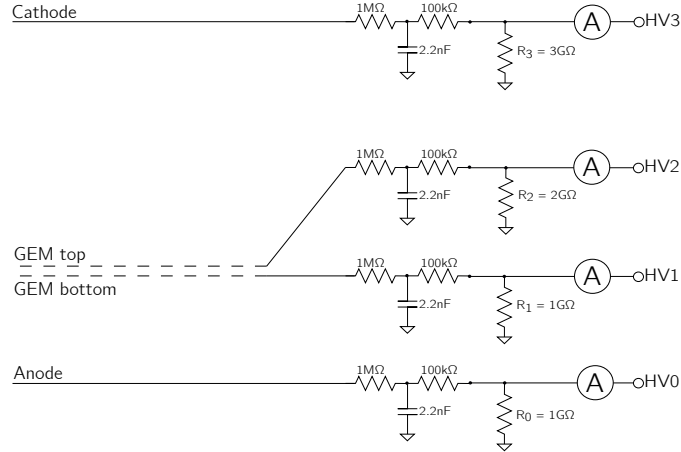


Figure 3.2: Powering scheme for the single-GEM detector: each electrode is powered individually using a CAEN 1471H 4-ch HV power supply

3.1.1 Experimental setup

The tests have been performed irradiating the GEM prototype with a X-ray source. The powering system, described below, has been used to measure the currents drawn by the electrodes for different values of the electric fields and source rate. The detector has been operated with Ar/CO₂ 70/30 gas mixture.

HV System

The power supply that has been used is the N1471H [43], a 4-channel device produced by CAEN. Each channel can supply up to 5.5 kV/20 μ A with a precision of 1 nA on the monitored current. In "High Accuracy" mode, the maximum supported current is 2 μ A and the resolution is of 50 pA. The power module has been controlled via USB with a LabView software for real-time monitoring and storage of the voltage and current values.

Figure 3.2 shows the powering scheme used for the GEM detector. Each GEM electrode has been connected to a HV filter and to ground through a $G\Omega$ resistor. Since the power supply can not read negative currents, the constant current drawn by the $G\Omega$ resistor works as positive offset. This makes possible to read negative variations in the currents drawn by the GEM electrodes.

X-Ray Source

The *Amptek Mini-X Tube* [44] is a Ag-target X-ray generator. The beam profile is gaussian and the source emits in a 120° cone. The output power is modified by setting the input potential difference (10 - 50 kV) or current (5 - 200 μA), up to 4 W. The isopower curve is shown in Figure 3.4. Figure 3.3 shows the output spectrum of the source measured with the *Amptek X-123SDD* X-ray spectrometer [45], where the higher peak corresponds to the Ag K- α transition at 22 keV. The nominal output flux is $\sim 10^6$ counts per second/mm², at a distance of 30 cm at maximum power.

The X-ray tube is placed in a large copper box, that acts as a radiation shielding and a Faraday cage.

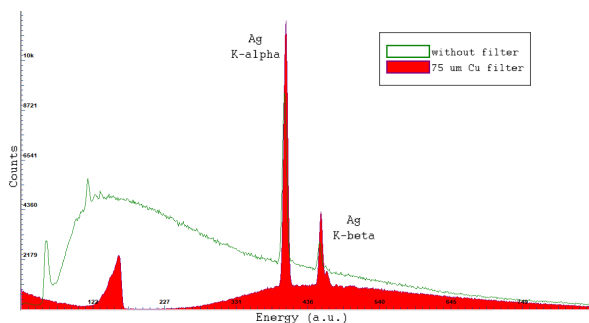


Figure 3.3: Mini-X Silver (Ag) X-Ray output spectrum at maximum power.

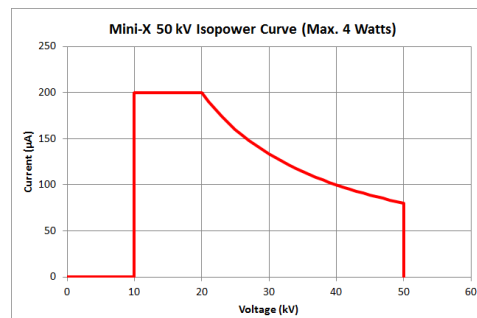


Figure 3.4: Amptek Mini-X tube isopower curve [44].

3.2 Experimental procedure and results

After the assembly, the GEM prototype was flushed with the gas mixture Ar/CO₂ 70/30 for several hours and placed vertically in the x-ray box, at short distance (about 10 cm) from the source. The four electrodes were connected to the power supply and the voltage was slowly ramped up. Pollution and dust introduced in the detector during the assembly caused some discharges, that occurred mainly between the top and bottom sides of the GEM foil. Once a stable environment was reached, the amplification foil was safely operated at high electric fields (up

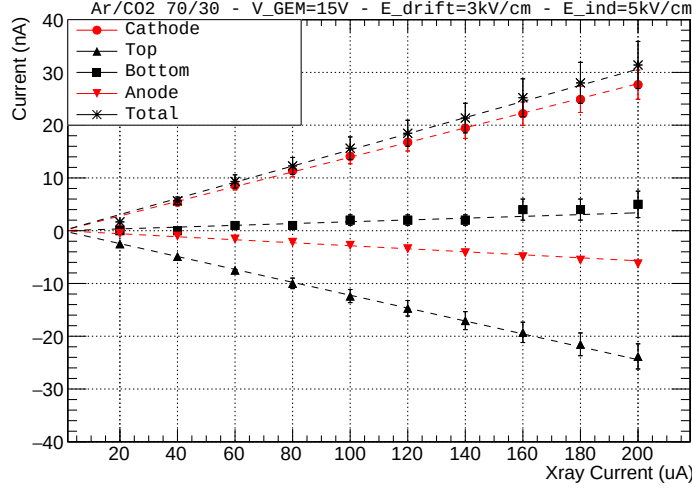


Figure 3.5: Currents induced on the GEM electrodes as a function of the x-ray tube current, at constant drift and amplification field.

to 100 kV/cm). The pressure, temperature and humidity level in the laboratory were monitored using a weather station.

Figure 3.5 shows the currents induced on the GEM electrodes for different values of the x-ray tube current, i.e. for different values of the incident flux, while the tube voltage was kept constant at $V_{\text{xray}} = (10 \pm 0.1)$ kV. The detector was powered so that the drift field and the amplification field were both 3 kV/cm and the induction field was 5 kV/cm. The current induced on each electrode by the source was evaluated as the difference between the average current drawn with the source on and the average current drawn with the source off, keeping the detector powered, in order to cancel out the average dark current and the constant offset introduced by the resistor connected to ground (Figure 3.2). The currents were averaged over a 10 s - long time interval.

$$\langle I \rangle = \langle I_{\text{GEM ON, source ON}} \rangle - \langle I_{\text{GEM ON, source OFF}} \rangle \quad (3.1)$$

The total current reported in Figure 3.5 is given by:

$$I_{\text{tot}} = (|I_{\text{cathode}}| + |I_{\text{top}}| + |I_{\text{bottom}}| + |I_{\text{anode}}|)/2 \quad (3.2)$$

and provides an indication on the total charge produced in the gas volume. Because of the low value of the amplification field, it is possible to assume that the response

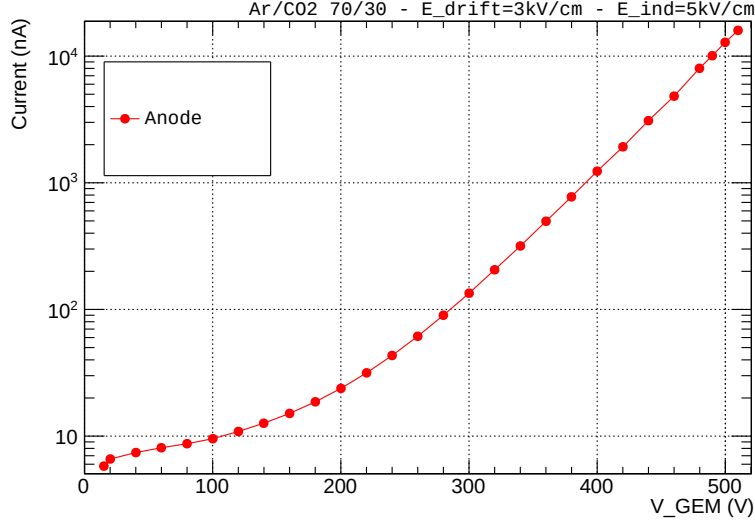


Figure 3.6: Absolute value of the current drawn by the anode as a function of V_{GEM} , at constant induction (5 kV/cm) and drift (3 kV/cm) field, normalized with respect to I_{xray} . The x-ray tube was operated at constant $V_{\text{xray}} = 10$ kV, while I_{xray} varied with V_{GEM} in order to avoid discharges.

of the detector in these conditions is due to primary ionization processes, without amplification. The linearity of the ionization current with respect to the incident flux has been exploited for the gain measurement and the experimental procedure described above has been used to study the dependence of the induced currents on the amplification, drift and induction fields.

3.2.1 Gain and collection efficiency

The multiplication factor, or *nominal* gain, of a gaseous detector is the total number of charges produced per single primary electron, while the measurable (or *effective*) gain is the ratio between the primary ionization charge and the charge collected on the electrodes. Since the charge collection is influenced by several factors, such as the geometrical acceptance of the electrodes or electric fields magnitude, *effective* and *nominal* gains differ by a factor named *collection efficiency*.

For low values of the amplification field (below $E_{\text{amp}} \simeq 8$ kV/cm), the GEM foil

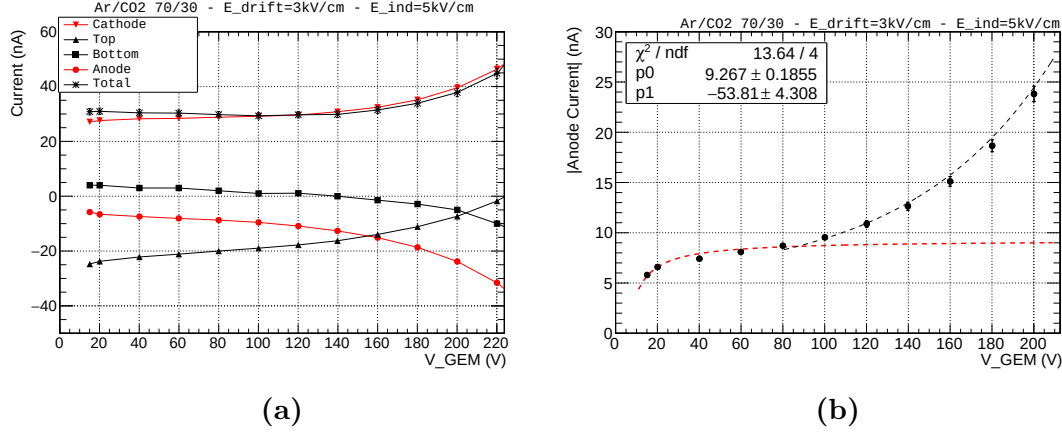


Figure 3.7: Currents drawn by the GEM electrodes as a function of the amplification field for Ar/CO₂ 70/30 gas mixture at constant induction (5 kV/cm) and drift (3 kV/cm) field, at maximum X-ray tube power (left). Detail: current drawn by the anode for low values of the amplification field. The red saturation curve indicates the effect of the collection efficiency (right).

can be assumed to work as a ionization chamber with nominal gain $G_0 = 1$. The current induced on the anode in these conditions is called the *ionization current*. Figure 3.6 shows the current drawn by the anode, in absolute value, as a function of the voltage applied to the GEM foil (V_{GEM}), while the induction and the drift fields were kept constant at $E_{\text{ind}} = 5$ kV/cm and $E_{\text{drift}} = 3$ kV/cm. At $E_{\text{amp}} \sim 0$, most of the ionization charge produced in the drift gap is collected by the GEM top electrode and does not reach the induction gap to be collected at the anode. A slight ionization in the induction gap induces a small positive current on the GEM bottom electrode. A detailed view of the currents drawn by all the electrodes for low values of V_{GEM} is given in Figure 3.7a. At low V_{GEM} , the drift gap (defined by the cathode and the GEM top) and the induction gap (defined by the GEM bottom and the anode) work as independent ionization chambers, with the positive ions motion inducing a positive current on the higher potential electrode, while the electrons move towards the anodic plane inducing a negative current.

As V_{GEM} increases, the number of electrons reaching the induction gap increases and the current induced on top electrode changes from negative to positive values because of drift motion of the positive ions produced in the holes. Moreover, the

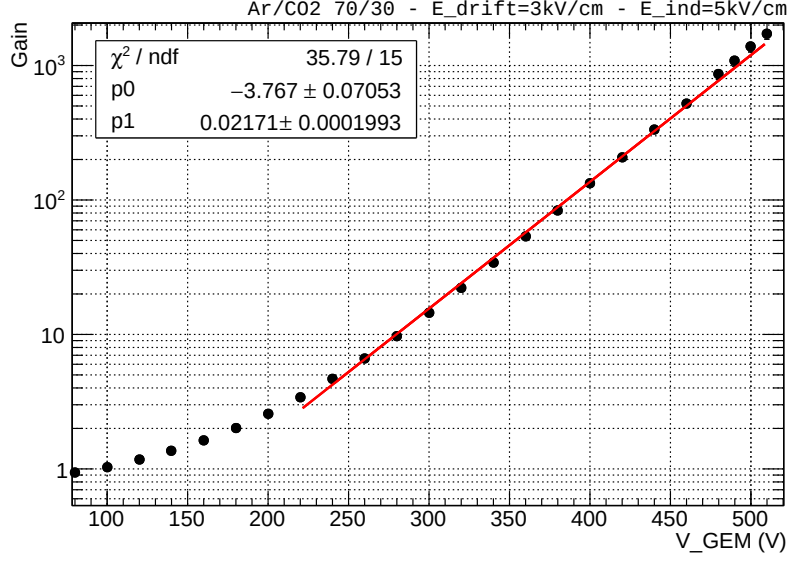


Figure 3.8: Gain as a function of VGEM.

total current, which is almost constant for $V_{\text{GEM}} < 140$ V, starts to increase. The exponential increase of the current indicates the avalanche multiplication of the charges in the holes. Figure 3.7b shows a detailed view of the current drawn by the anode, in absolute value. In order to evaluate the ionization current induced on the anode, the plot is fitted with a saturation curve (red dashed) given by:

$$I_{\text{anode}} = \alpha + \beta \frac{1}{x} \quad (3.3)$$

where $x = V_{\text{GEM}}$ varies in the interval $[0; 100]$ V. The value of the fitting parameter $\alpha = (9.26 \pm 0.19)$ nA gives an estimation of the ionization current induced at maximum collection efficiency, before that the GEM starts the amplification process.

The plots in Figure 3.7 were obtained operating the x-ray tube at maximum power, in order to exploit the sensibility of the amperometer embedded in the CAEN 1471H power supply. At $V_{\text{GEM}} > 140$ V, the x-ray irradiation at maximum rate caused discharges in the detector. Exploiting the linearity of the induced current (Figure 3.5), the plot in Figure 3.6 was obtained varying the x-ray tube I_{xray} with V_{GEM} , in order to avoid discharges. The current values measured at high V_{GEM} (i.e. low I_{xray}) were normalized with respect to the maximum X-ray tube

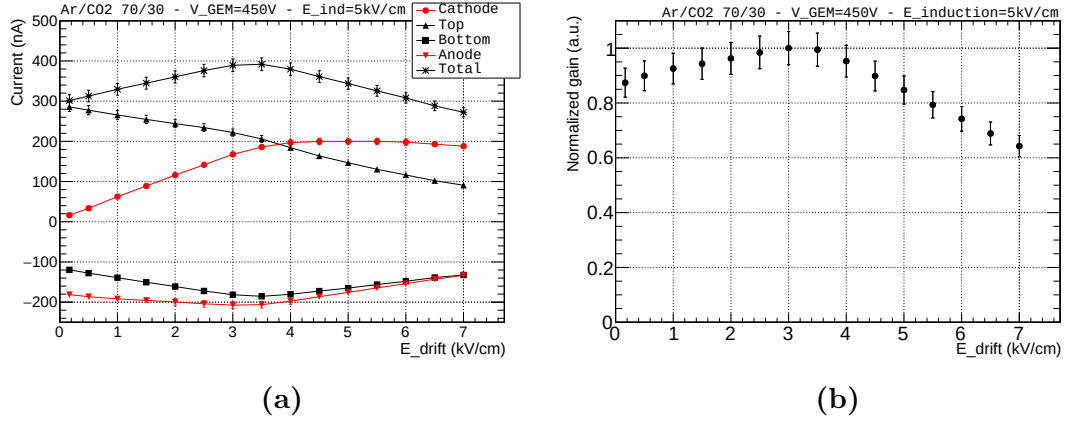


Figure 3.9: Currents drawn by the GEM electrodes (left) and normalized gain (right) as a function of the drift field for Ar/CO₂ 70/30 gas mixture at constant induction (5 kV/cm) and amplification (90 kV/cm) field. The X-ray tube irradiation rate was kept constant setting $I_{\text{xray}} = 20\mu\text{A}$ and $V_{\text{xray}} = 10\text{kV}$.

power. This procedure allows to evaluate the effective gain of the GEM detector:

$$G = \frac{I_{\text{anode, amp}}(V_{\text{GEM}})}{I_{\text{anode, ionization}}} \cdot \frac{I_{\text{xray, max}}}{I_{\text{xray}}(V_{\text{GEM}})} \quad (3.4)$$

where $I_{\text{anode, amp}}$ is the average current induced on the anode depending on the the amplification field, $I_{\text{xray}}(V_{\text{GEM}})$ is the value of the x-ray tube current set for the measurement, $I_{\text{anode, ionization}}$ is the ionization current given by the α parameter in Eq. 3.3 (Figure 3.7b) and $I_{\text{xray, max}}$ is the maximum value for x-ray tube current, which was used to measure the ionization current. The single-GEM gain curve is reported in Figure 3.8 and it is fitted with an exponential function at high V_{GEM} . The result is consistent with the gain measured by Bachmann et al. [46] using a similar single-GEM prototype with a different experimental procedure and the gain curve is compatible with the one measured by Bencivenni as a benchmark for the 50 μm Micro-RWELL detector [31].

3.2.2 Effect of the drift field

The curve in Figure 3.9a shows the dependence of the currents induced on all electrodes on the drift field magnitude E_{drift} , at constant induction (5 kV/cm) and

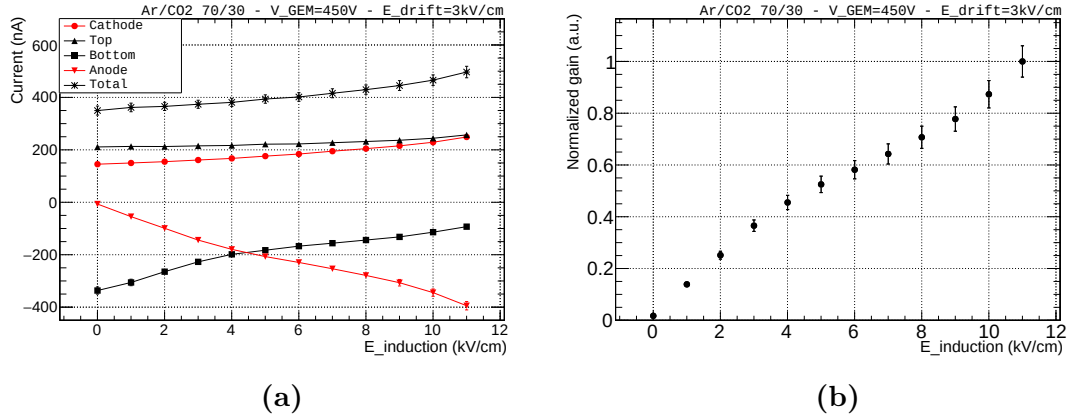


Figure 3.10: Currents induced on the GEM electrodes (left) and normalized gain (right) as a function of the induction field for Ar/CO2 70/30 gas mixture at constant drift (3 kV/cm) and amplification (90 kV/cm) field. The X-ray tube irradiation rate was kept constant setting $I_{\text{xray}} = 20\mu\text{A}$ and $V_{\text{xray}} = 10\text{kV}$.

amplification (90 kV/cm) and at constant x-ray rate. The ion feedback in the drift gap, which is proportional to the current induced on the cathode (I_{cathode}), increases with E_{drift} and saturates at $E_{\text{drift}} > 4$ kV/cm. Moreover, the charge collected on top electrode is the sum of the positive ions produced in the holes and the electrons not reaching in the amplification zone: as E_{drift} increases, the contribution of electrons to I_{top} become relevant. The total current indicates that the number of electrons reaching the amplification zone has a maximum at $E_{\text{drift}} = 3 \div 3.5$ kV/cm, which is considered a good operational value for GEM detectors.

The normalized gain as a function of the drift field is reported in Figure 3.9b. Since G is proportional to the current collected on the anode, the gain curve confirms that the maximum collection efficiency is reached for $E_{\text{drift}} \sim 3$ kV/cm.

3.2.3 Effect of the induction field

The currents induced on all electrodes as a function of the induction field magnitude E_{ind} are shown in Figure 3.10a, obtained at constant drift (3 kV/cm) and amplification (90 kV/cm) field and at constant x-ray rate. The current induced

on the GEM bottom increases almost linearly with E_{ind} ; thus the fraction of the electrons produced in the avalanches which are collected on the bottom GEM and then "missed" can be reduced increasing E_{ind} . As a consequence, the electronic current collected on the anode increases, so that a high induction field enhances the transparency of the GEM foil. The total current, which is expected to be constant, increases slightly with E_{ind} because of the influence of the induction field on the amplification field lines. At induction field above 8 kV/cm, the I_{tot} increases with a higher slope because of the multiplication in the induction gap: this mode of operation is considered unsafe because discharges in the induction gap would damage the readout electronics.

Figure 3.10b shows the normalized gain as a function of the induction field. As discussed above, the effect of the induction field is to enhance the transparency of the amplification stage, reducing the number of electrons collected on the GEM bottom. Moreover, the induction field slightly affects the amplification field lines, increasing the gain of the GEM foil.

3.3 Conclusions

The test setup developed for the single-GEM detector makes it possible to measure the current induced by x-rays on all the powered layers of the detector and can be exploited to carry out similar tests on different MPGD prototypes. The results of preliminar tests on the FTM v.4 detector will be presented in the next chapter, together with the limitations of the x-rays test setup. The gain curve of the 50 μm -thick single-GEM has been measured as useful benchmark for further tests on the FTM v.4. Since the main limitation of a single amplification stage detector is in the effective gain, in the future a thick-GEM prototype with a 125 μm amplification foil will be characterized with the same procedure, in order to consider the thick-WELL as an optional solution for future FTM prototypes.

Chapter 4

Preliminary tests on the FTM prototype

The new prototype of the Fast Timing Micro-pattern gaseous detector has been described in Chapter 2. It was assembled in 2017 at CERN and preliminary tests with x-ray were performed in Bari during the first months of 2018.

The experimental setup used is the same as described in Chapter 3 for the gain measurement of the single-GEM detector. Each layer of the FTM prototype, consisting of three resistive electrodes, here named *drift*, *top* and *bottom*, was powered using a CAEN 1471H 4-ch HV power supply which worked as a 4-channel amperometer with 50 pA resolution, as schematically shown in Figure 4.1. The $G\Omega$ resistors connected to ground provided a positive offset current to each channel of the power supply, in order to measure negative variations in the currents drawn by the FTM electrodes.

After the transport to Bari, the FTM prototype was flushed with Ar/CO₂ 70/30 gas mixture for several hours at 5 l/h input flux, in order to clean the detector.

4.1 Powering and stability

Due to the similarity between the amplification layers of the first FTM prototype and the amplification layers used in the new prototype (thickness $50\mu m$, holes diameter $\sim 70\mu m$, pitch $140\mu m$), we expected to power the resistive elec-

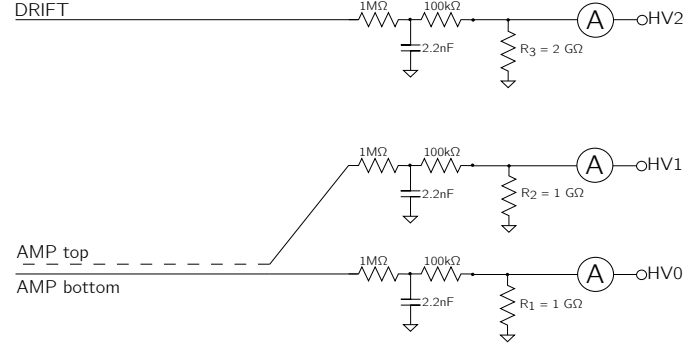


Figure 4.1: Powering scheme for one single layer of the FTM v.4 detector: each electrode is powered individually using a CAEN 1471H 4-ch HV power supply

trodes at the same voltage values used to characterize the FTM v.1, which was safely operated at 120 kV/cm amplification field ($V_{\text{amp}} = V_{\text{top}} - V_{\text{bottom}} = 600$ V) [34, 35]. For the HV test, the layers of the FTM v.4 prototype were powered one at a time; Figure 4.2 shows the currents drawn by the electrodes of the FTM v.4 as a function of time at different voltage settings. The offset currents are related to the $G\Omega$ resistors connected to ground, whose nominal values are $2 G\Omega$ for the drift electrode and $1 G\Omega$ for both top and bottom electrodes. The layers had different behaviours, becoming unstable at different values of the amplification field, while the drift field was kept constant at 3 kV/cm ($V_{\text{drift}} - V_{\text{top}} = 75$ V). When unstable, the currents drawn by the electrodes reached peaks of ~ 100 nA of amplitude which occurred even after 1 hour of powering. Layer 1 and 4 were stable at $E_{\text{amp}} = 110$ kV/cm, while Layer 2 and 3 were operated at $E_{\text{amp}} = 120$ kV/cm, with small variations (few nA) in the currents drawn.

Using a Samtek-to-LEMO connector, the bottom readout plane was connected to an ORTEC 142PC preamplifier [47] and to an ORTEC 474 amplifier and shaper [48] in order to see signals on the oscilloscope. The signals picked up from the all the strips were hidden by a large noise (~ 100 mV peak-to-peak) coming from the power grid of the laboratory.

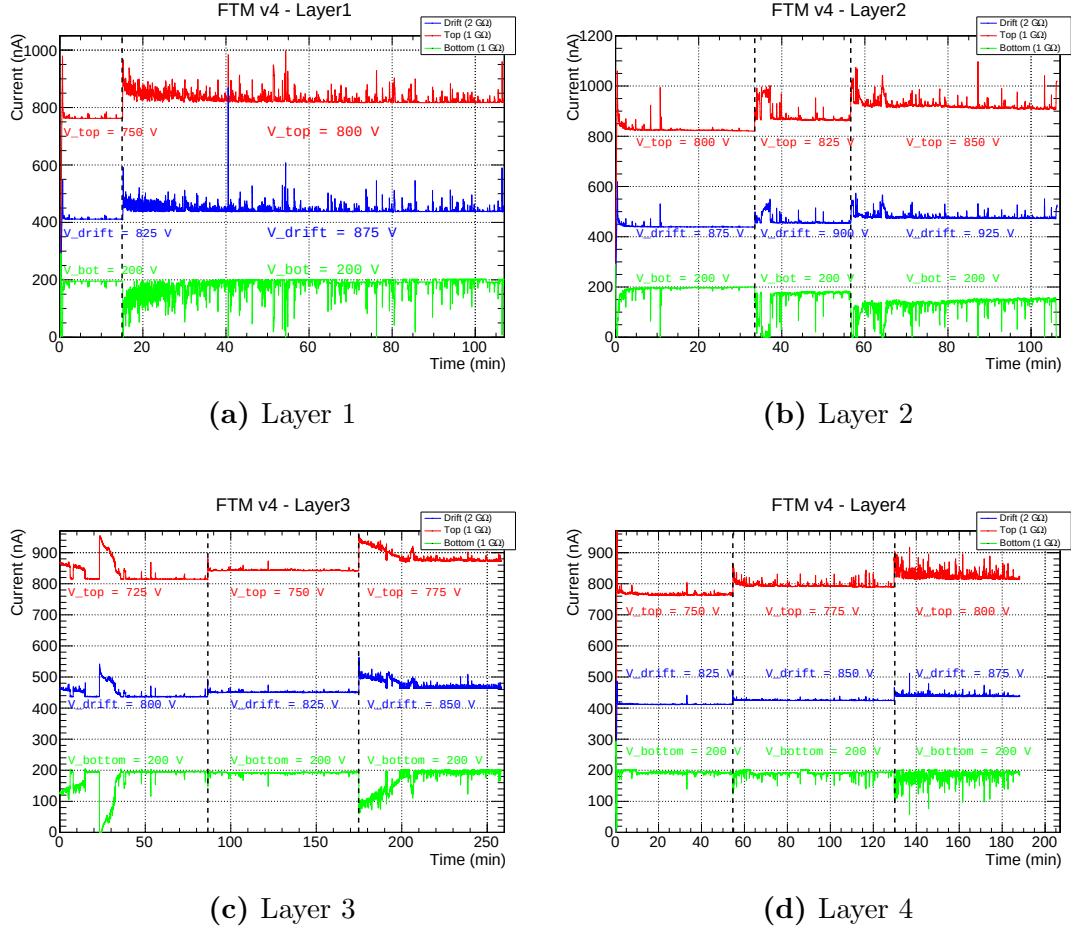


Figure 4.2: Currents drawn by the electrodes of the FTM v.4 as a function of time at different voltage settings.

4.2 Detection of X-rays

4.2.1 Linearity with X-ray intensity

The detector was placed in the x-ray box and irradiated with the Mini-X tube. The procedure described in Chapter 3 was exploited to measure the current drawn by the FTM resistive layers as:

$$\langle I \rangle = \langle I_{\text{FTM ON, source ON}} \rangle - \langle I_{\text{FTM ON, source OFF}} \rangle \quad (4.1)$$

where the currents were averaged on a 60 s - long time interval.

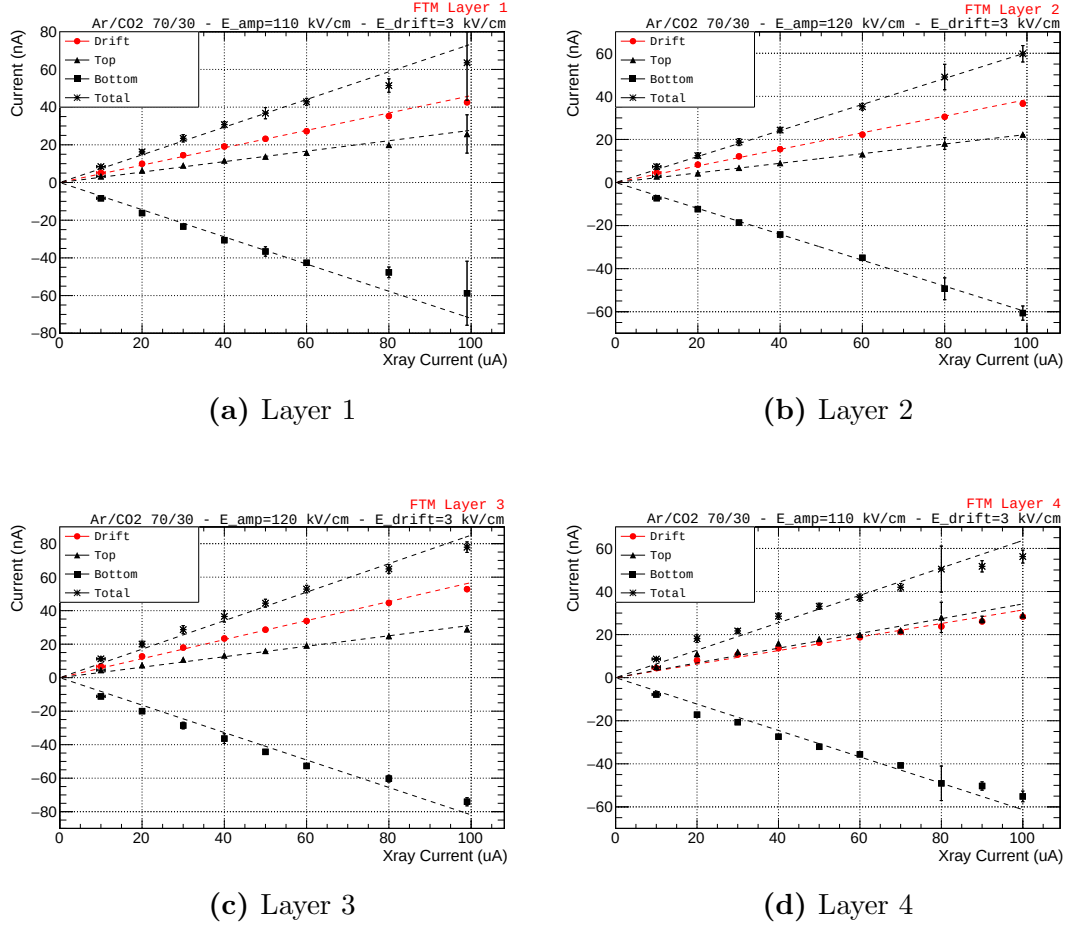
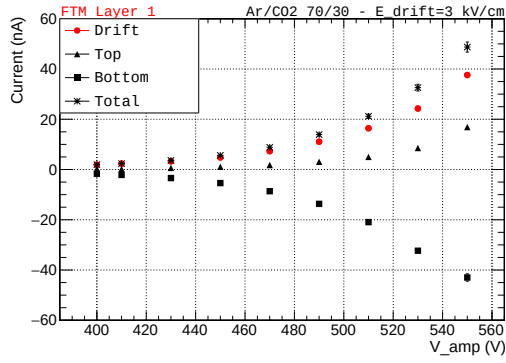


Figure 4.3: Currents drawn by the electrodes of the FTM v.4 as a function of the x-ray tube current, at constant drift (3 kV/cm) and amplification (110 ÷ 120 kV/cm) field.

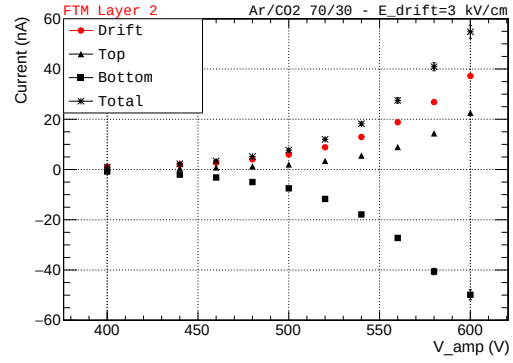
Figure 4.3 shows the currents induced on the FTM electrodes for each layer as a function of the x-ray tube current, i.e. by varying the incident flux, while the tube voltage was kept constant at $V_{\text{xray}} = (40 \pm 0.1)$ kV. The detector was powered so that the drift field was 3 kV/cm and the amplification field was 110 ÷ 120 kV/cm depending on the layer. The total current reported in Figure 4.3 is given by:

$$I_{\text{tot}} = (|I_{\text{drift}}| + |I_{\text{top}}| + |I_{\text{bottom}}|)/2 \quad (4.2)$$

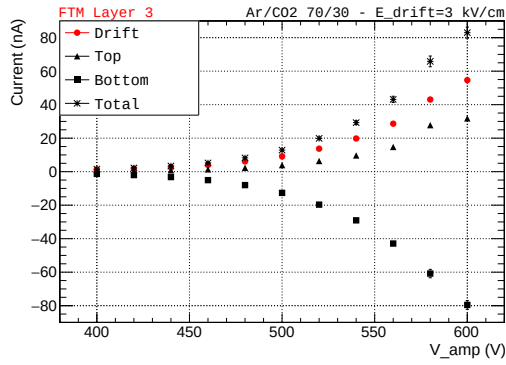
and indicates the total charge produced in the gas volume, which turns out to be fairly proportional to the x-ray rate. It is noticeable that the sum of the induced current is almost zero, indicating that the resistive layers are correctly insulated.



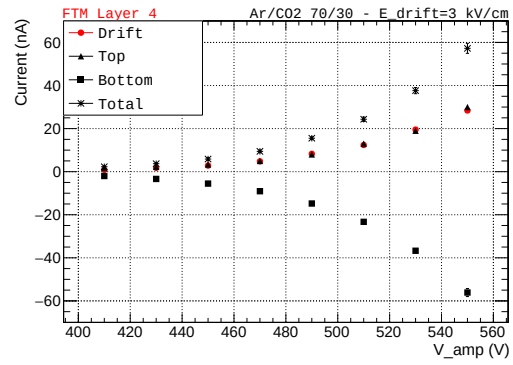
(a) Layer 1



(b) Layer 2



(c) Layer 3



(d) Layer 4

Figure 4.4: Currents drawn by the electrodes of the FTM v.4 as a function of the voltage applied on the amplification layer, at constant drift field (3 kV/cm), at maximum X-ray tube power.

4.2.2 Townsend avalanche

The goal of the preliminary tests was the evaluation of the multiplication factor of one single layer in the FTM v.4, which required the measurement of the ionization current at low amplification field. As discussed in Chapter 3, the ionization current in the GEM detector was defined as the current drawn by the readout plane (the anode) at $V_{\text{GEM}} \leq 100$ V (see Figure 3.7b). For the WELL layers of the FTM, the ionization current is defined as the current induced on the resistive layer placed under the amplification foil. At $V_{\text{amp}} \leq 350$ V, the current drawn by

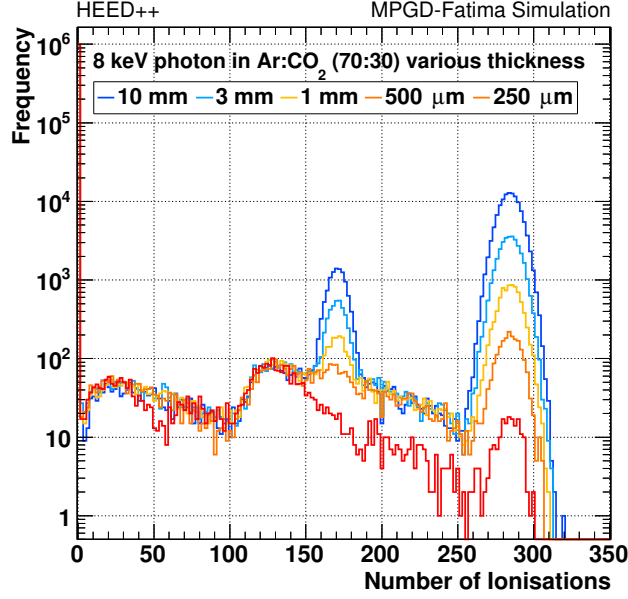


Figure 4.5: Frequency of events as a function of the number of primary ionizations produced by a 8 keV photon crossing the gas gap filled of Ar/CO₂ 70/30, simulated for different values of thickness [49].

the bottom electrodes at maximum x-ray power were comparable with the current fluctuations (~ 1 nA), so that it was not possible to measure the current induced at low field. In fact, at 350 V we already expected a considerable amplification ($G \sim 100$). Figure 4.4 shows the currents induced on all the electrodes for each layer with the variation of the amplification field. The exponential growth of the total current at high amplification fields indicates the Townsend multiplication of the primary ionization charge produced in the gas volume. However we could not determine the gain of the detector.

4.2.3 Limitations of the experimental setup

The use of X-rays to test the FTM detector is not an optimal choice because of the detector geometry and composition. The FTM detector, in contrast to most other Micro Pattern Gaseous Detectors (MPGDs), does not have a large drift gap (3 mm - 1 cm). Therefore the conversion probability of photons crossing

the gas gap is lower and the highly ionizing electrons produced ($E \sim \text{keV}$) are not stopped inside the gas. Since their range is typically of 1 mm [2], not all their energy is converted in the gas and the amount of ionizations is subject to statistical fluctuations. Figure 4.5 shows the number of ionizations produced by a 8 keV photon in a gas gap of 250 μm , 500 μm , 1 mm, 3 mm and 1 cm filled of Ar/CO₂ 70/30. In a *standard* GEM detector the thickness of the drift gap is of 3 mm and an incoming 8 keV photon is totally absorbed. In this case, the average number of electrons produced is given by:

$$n_p = \Delta E_{\text{photon}} \cdot \left(\frac{0.7}{W_{i_{\text{Ar}}}} + \frac{0.3}{W_{i_{\text{CO}_2}}} \right) \simeq 8 \cdot 10^3 \text{eV} (0.7/26 + 0.3/33) \text{eV}^{-1} = 288 \quad (4.3)$$

where the W_i is the average energy to produce an electron-ion pair in the gas (see Table 1.1). For a 250 μm -thick gas gap, which is the case of the FTM v.4 prototype, the probability for a 8 keV photon conversion followed by a full deposition of the photon energy in the gas volume ($n_p \simeq 290$ ionizations) is drastically reduced, and events with lower ionization dominate, prohibiting to observe the peak experimentally. Moreover, the FTM detector is fully resistive and does not have a Cu electrode that acts as an X-ray converter for the spectrum emitted by the X-ray source to the characteristic Cu X-ray peaks at 8 and 9 keV. Low energy X-rays have higher absorption cross section in the gas [2]. The 20 and 22.5 keV X-rays from the Amptek Mini-X Ag-target tube have much lower probability to interact in the gas gap. The FTM detector has thin Cu readout electrodes external to the detector, X-rays converted in these thin strips however have to pass through ~ 3 mm of top PCB, which drastically reduces their abundance.

A test setup with atmospheric muons would be not suitable for the characterization of small prototypes, due to the small rate (100 Hz/ m^2) and inherent fluctuations of the energy deposit, which preclude their use for gain measurements.

In order to overcome these problems, the setting up of a Ultra Violet (UV) laser facility has been proposed. The UV laser can ionize on impurities in the gas inside the detector through two-photon and three-photon processes [41], entering in the sensitive volume through a quartz window.

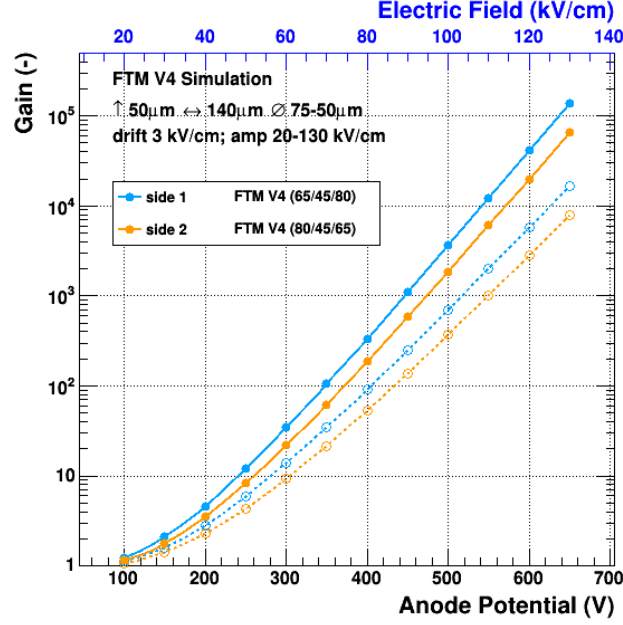


Figure 4.6: Nominal gain of the biconical holes of the FTM v.4 detector, as a function of the amplification field, at constant drift field (3 kV/cm), simulated for two different orientations of the holes [49].

4.3 Gain simulation

Even if it was not possible to measure the effective gain of the FTM v.4 prototype, an estimation can be obtained by simulations for comparison with the $50\text{ }\mu\text{m}$ single-GEM and the $50\text{ }\mu\text{m}$ μ -RWELL detector [31]. The gain of the WELL layer depends on the depth of the holes, on their size and on their shape. The holes of the FTM v.4 amplification foils have been obtained by chemical etching of a DLC/Polyimide/Cu FCCL foil and have double-conical shape with a diameter of about $80/45/60\text{ }\mu\text{m}$ respectively (see Figures 2.11a and 2.11b). Figure 4.7 reports the results of a COMSOL [9] simulation for the electric field in the holes. The simulation was performed for two different geometry of the holes, illustrated in Figure 4.8: the etching process led to large holes in the DLC (i.e. the side facing the drift gap) and small holes in the Cu (i.e. the side stacked on the resistive layer), while an inverted situation would have produced a stronger electric field inside the holes.

The simulated gain of one layer of the FTM detector as a function of the amplification field is reported in Figure 4.6. At 120 kV/cm amplification field, with the 80/45/60 μm holes, we expect a nominal gain of about 10^4 , so that the charge of a single electron reaching the amplification layer can produce a signal of 1.6 fC.

4.4 Conclusions

The preliminary tests on the FTM v.4 prototype revealed that the x-ray test setup is not suitable for the characterization of gaseous detector which have a small drift gap and no copper layers facing the gas volume. For future tests on Fast Timing Micro-pattern gaseous detectors, the setting up of a UV laser facility is planned, to be used to test the detectors before moving to expensive test beam campaigns. On the other hand, it is necessary to develop a readout electronics which can amplify the small signals produced by the FTM with good time resolution: the FATIC readout chip has been developed in Bari for this purpose. The first version of the chip has been characterized and the results are reported in the next chapter.

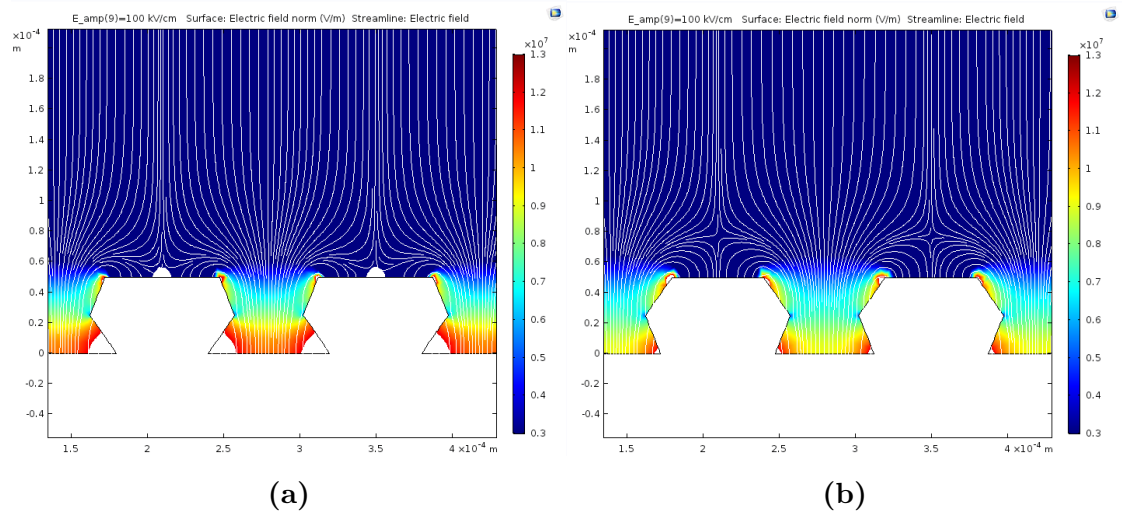


Figure 4.7: Electric field lines in the FTM v.4 amplification foils, for two different orientations of the holes, simulated with COMSOL Multiphysics [49].

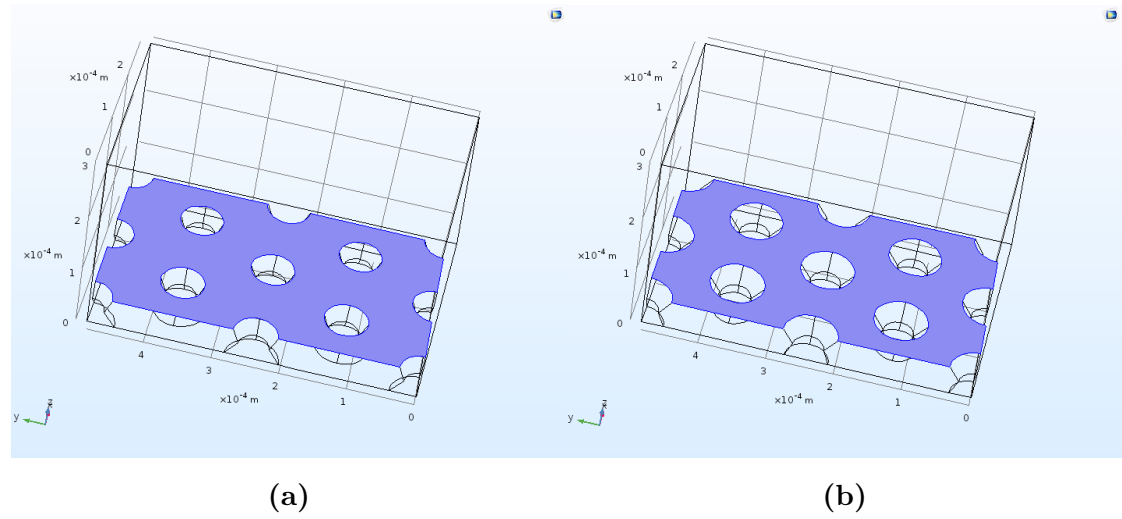


Figure 4.8: Holes geometry used for the COMSOL simulation [49].

Chapter 5

Fast Timing Readout Electronics

5.1 Introduction

The development of new electronics for fast timing MPGDs is driven by the need to acquire small signals (~ 1 fC) with high time resolution (~ 100 ps). Although several front-end chips have been designed for HEP applications, it is difficult to combine low input charge with fast timing. To give an example, with *high* gain 20 mV/fC, a 1 fC charge pulse would result in a 20 mV voltage ripple, about the size of the typical low frequency noise picked up in the laboratory.

An example of fast gaseous detector electronics is an ultrafast front-end preamplifier-discriminator chip called NINO, that has been developed in 2004 for the ALICE time-of-flight detector (composed by Multigap Resistive Plate Chamber (MRPC)) [50]. MRPCs have a time resolution down to 60 ps [51] and a gain $10^5 \div 10^8$ for a single electron crossing the gap (corresponding to a signal of $10 \text{ fC} \div 10 \text{ pC}$), so that the NINO front-end is designed to digitize fast signals (~ 100 ps) with low jitter (< 25 ps), with no need to provide a high gain amplification in the electronics. On the other hand, the electronics designed for MPGDs (eg triple-GEM detectors, whose typical gain is $\sim 10^4 - 10^5$) can digitize small signals. It is the case of the VFAT chip, that has been designed for the readout of sensors in the TOTEM experiment at the LHC [52]. The main limit of using VFAT for the acquisition of fast signals is the jitter introduced by the VFAT clock (40Mhz). It is therefore clear that it is necessary for the development of the FTM to have a

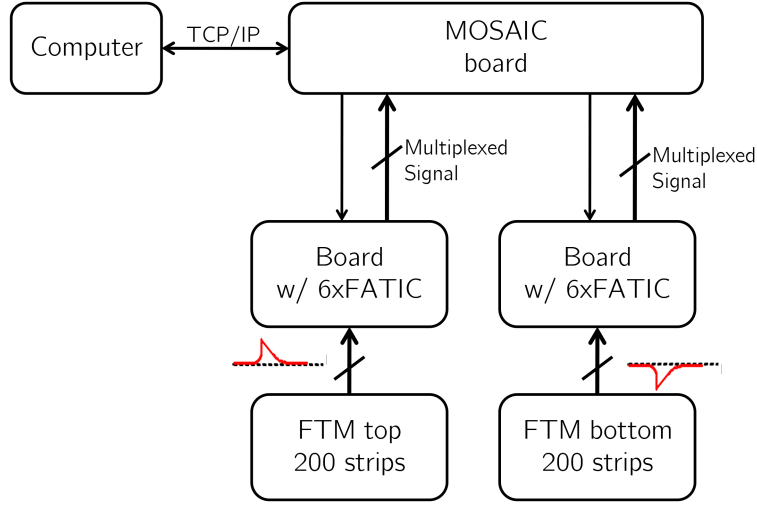


Figure 5.1: Block diagram of the DAQ system

low noise electronics that can amplify small signals maintaining the time resolution of the detector. Compatibility with both positive and negative signals is also required, in order to read the induced charge on top and bottom FTM readout planes. To match all these requirements, the INFN-Bari CAD Team developed the FAsT Timing Integrated Circuit (FATIC).

5.2 Electronic Setup

The Data Acquisition (DAQ) system for the FTM detector is shown in Figure 5.1. The FATIC has the function of extracting and digitizing the charge and time information from the FTM analog signals. The data are then synchronously acquired by the MODular System for Acquisition, Interface and Control (MOSAIC) board, that will be described later. The board is also used to write the parameters in the FATIC registers (e.g. comparator thresholds).

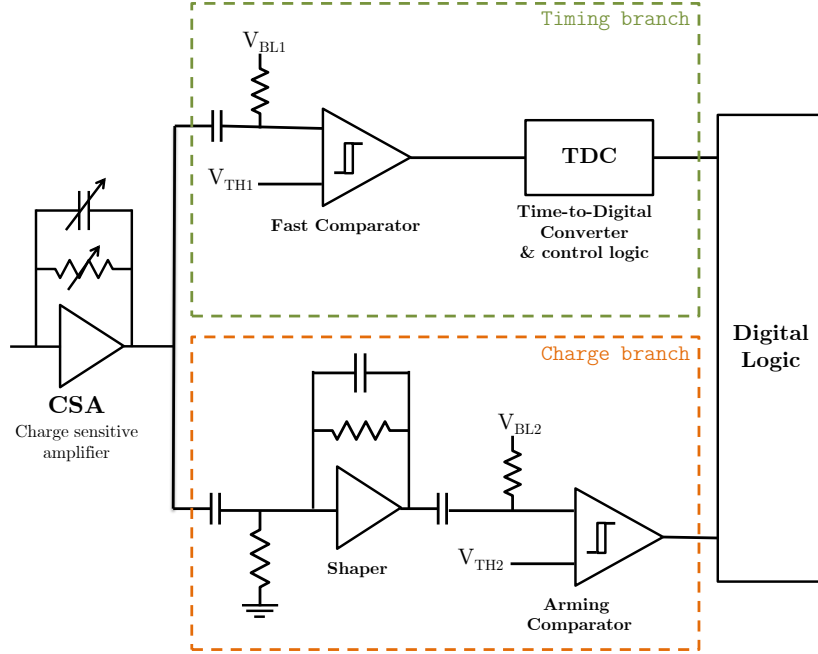


Figure 5.2: FATIC chip architecture

5.2.1 Fast Timing Integrated Circuit (FATIC)

The Fast Timing Integrated Circuit (FATIC) is a front-end Application Specific Integrated Circuit (ASIC) that incorporates a fully integrated amplifier, shaper and discriminator circuit. It supports 32 analog input channels, plus one channel for test purposes. The chip has been designed by INFN-Bari CAD Team. In the following, the first prototype of the chip will be described, illustrated by Figure 5.2 which refers to a single channel. The input signal is amplified by a Charge Sensitive Amplifier (CSA) and its output is splitted into two branches: a “timing” branch and a “charge” branch. The timing branch contains a *Fast Comparator* (FC) and a Time-to-Digital Converter (TDC) and it is designed to measure the arrival time of the input signal with low jitter (~ 300 ps). The global FC threshold is set by a 8-bit Digital to Analog Converter (DAC) whose Least Significant Bit (LSB) corresponds to 2.5 mV; the baseline voltage (V_{BL1} in Figure 5.2) is 500 mV, that is equivalent to ~ 220 DAC units (from calibration), so that the threshold can be

Table 5.1: Details of the FATIC characteristics

CSA			TDC	
Peaking time*		7.3ns	Resolution	5-bit fine / 16-bit coarse
Time jitter*		300ps@1fC input charge	Ref. Clock	320 MHz
ENC*		$18.2e^- / pF \cdot C_{in}(pF) + 235.5e^-$	Time res.	100 ps
Current/Ch*		1.3mA	Fast Comparator	
Signal Polarity		positive & negative	Global Th.	8-bit DAC, LSB = 2.5 mV
Gain	High	50mV/fC	Local Th.	6-bit DAC, LSB = 2 mV
	Low	10mV/fC	Arming Comparator	
Shaper			Global Th.	8-bit DAC, LSB = 2.3 mV
Peaking time	100 ns		Local Th.	6-bit DAC, LSB = 1.725 mV

*simulation in high gain mode with $C_{in} = 15pF$

calculated as follows:

$$Th_{FC} = (DAC \text{ units} - 220) * 2.5 \frac{mV}{unit} \quad (5.1)$$

The TDC consists of a 16-bit coarse and a 5-bit fine counter supporting 33 input channels. It works with a 320 MHz reference clock and has a nominal resolution of 100 ps. The charge branch is composed by a shaper and a comparator circuit (here named *Arming Comparator* (AC)). The nominal shaping time constant is 100 ns and was chosen to be not adjustable. The global AC threshold is set a 8-bit DAC with $LSB = 2.3 \frac{mV}{unit}$. For both the comparatos, a 6-bit threshold-equalization DAC per channel allows the user to correct the thresholds. The CSA can be set to accept positive or negative input signals and can operate in two modes: low-gain mode and high-gain mode, with an adjustable recovery time. The FATIC's main features are summarized in Table 5.1. The digital output signal of each channel is the logic AND between the *Fast Comparator* and the *Arming Comparator* outputs. The Fast OR of all the 32 channels is also available to use e.g. as a trigger signal.

5.2.2 MOSAIC board

The MOdular System for Acquisition, Interface and Control (MOSAIC) is conceived for the testing of detectors and their related electronics. The board has been designed by INFN-Bari Electronic Design Team for the readout and testing of the

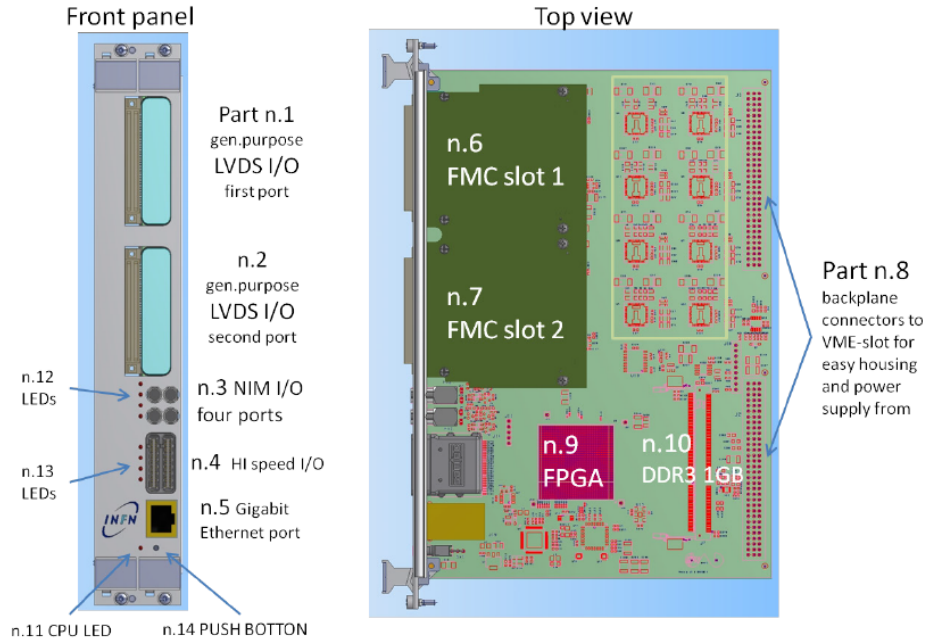


Figure 5.3: Main parts of MOSAIC board are enumerated in a mechanical drawing. LVDS I/O ports (n. 1 and 2); 4 X NIM I/O (n. 3); HI Speed I/O ports (n. 4); Ethernet plug (n. 5); 2 X FMC-LPC mezzanine slots (n. 6 and 7); Field Programmable Gate Array (n. 9); 1GB-DDR3 (n. 10); status LEDs (n. 11 - 13). Credit: [53]

pixel modules of the silicon tracker upgrade for the ALICE experiment at the LHC [53]. Its main component is a Field Programmable Gate Array (FPGA), whose firmware infrastructure provides the possibility to customize the system adding user modules. The main parts of the MOSAIC board are shown in Figure 5.3. The MOSAIC can read data through high speed serial links and it is equipped with slower input channels for general purpose Low Voltage Differential Signals (LVDS). The front panel of the board is equipped with four programmable multi purpose input/output (I/O) LEMO connectors compatible with NIM standard. The board contains two FMC-LPC (FPGA Mezzanine Card – Low Pin Count) mezzanine slots in order to provide additional connectivity to various device interfaces. A TCP/IP connection is provided for data transmission, control of operations and additional functions such as firmware upgrade, IP address configuration and board diagnostics at startup.

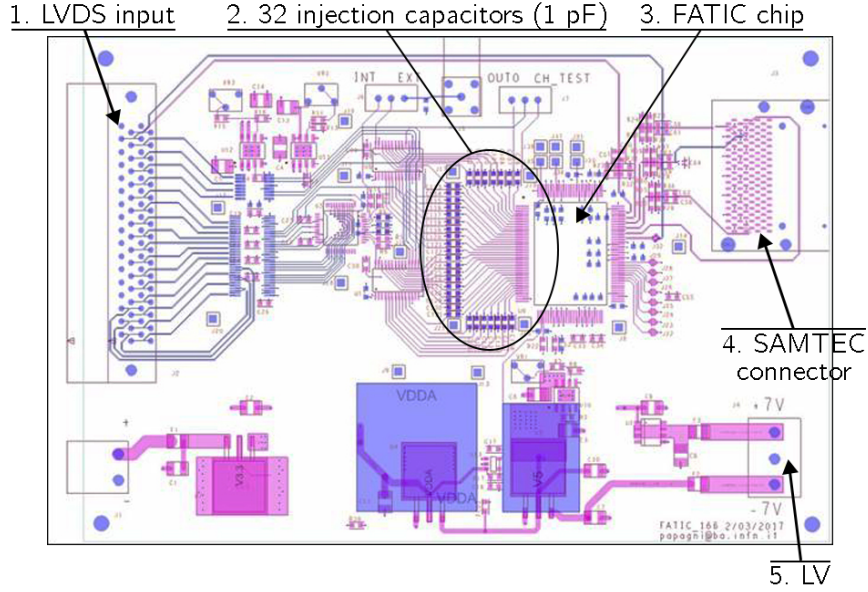


Figure 5.4: FATIC Test board schematic. LVDS input (n. 1); 32 X (1 ± 0.25) pF capacitors for pulse injection (n. 2); FATIC chip housing (n. 3); SAMTEC connector for high speed link to MOSAIC (n. 4); Low Voltage power supply connection (n. 5).

5.3 FATIC characterization

In order to understand the electronics when used with the detector, it is necessary to understand the electronics itself. It is also important to test the performances of the first version of the FATIC to plan the development of a second - improved - version. The first prototype of the FATIC has been characterized using the MOSAIC board and a test board, simulating the sensor. In the following the experimental setup and the measurements will be described.

5.3.1 FATIC Test Board

The test board is shown in Figure 5.4. It was connected to the MOSAIC board to read output digital signals and to write the test board registers. 32 capacitors ($C_{test} = 1 \text{ pF} \pm 0.25 \text{ pF}$) are used to provide detector-like signals to the FATIC input channels independently. Appropriately programming the MOSAIC board, the user writes the amplitude of a step signal in a DAC register. The pulse is

then sent to one channel at a time and the capacitor discharge generates the input pulse. The injected charge can be calculated as follows:

$$Q = 0.1 \frac{mV}{unit} * C_{test} * DAC \text{ units} \quad (5.2)$$

In this setup, the MOSAIC's NIM I/O ports can be set such that the trigger input signal and the fast-OR output signal are sent to an oscilloscope. This allows the user to evaluate the timing performance of the chip.

5.3.2 CSA: gain, noise, linearity

Each of the FATIC channels was tested by injecting N pulses and by counting the number of responses, for different values of the injected charge (set by programming the DAC, see Eq. 5.2). The number of digital output signals as a function of the injected charge follows a sigmoid curve. The example in Figure 5.5 refers to channel 15, with the CSA operating in High Gain mode. The *Fast Comparator* threshold was set at $\text{Thr} = 150$ DAC units, that corresponds to ~ -175 mV (Eq. 5.1). The *Arming Comparator* was disabled, so that only the timing branch was used. The sigmoid curve was fitted with the cumulative distribution function of a Normal Distribution with mean μ and variance σ^2 (Eq. 5.3).

$$\Phi(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^x e^{\frac{-(z-\mu)^2}{2\sigma^2}} dz = \frac{1}{2} \left[1 + \text{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right) \right] \quad (5.3)$$

The sigmoid curve measurement was repeated for all channels, in high gain mode, using two different values of the *Fast Comparator* (FC) threshold. Figure 5.6 shows the distribution of μ and σ for all channels, while the plots in Figure 5.7 refer to the same procedure with the CSA operating in low gain mode. The width of the distribution of the mean values (μ) is due to the threshold mismatch. The threshold-equalization DACs allow to correct the threshold mismatch, but the equalization procedure is feasible only in the presence of an input pulse generator (such as when using the test board). Thus, the implementation of an internal test circuit is planned for the second version of the FATIC chip.

The average standard deviation is given by Eq. 5.4 and it corresponds to the Equivalent Noise Charge (ENC); this estimation is consistent with the simulation

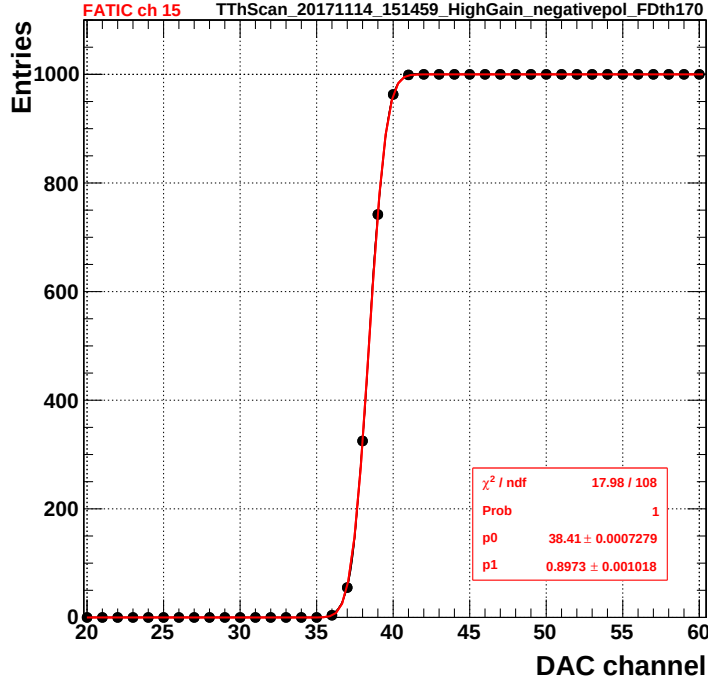


Figure 5.5: Sigmoid curve for channel 15 in High Gain mode.

results ($508 e^-$, see Table 5.1).

$$\langle \sigma_{\text{timing branch}} \rangle = 1.043 \text{ DAC unit} \simeq 0.1043 \text{ fC} \simeq 652 e^- \quad (5.4)$$

The gain of the CSA can be calculated from Eq. 5.5 and the obtained values are reported in Figure 5.8.

$$G = \frac{Th_1 - Th_2}{\mu_1 - \mu_2} \left(\frac{mV}{fC} \right) \quad (5.5)$$

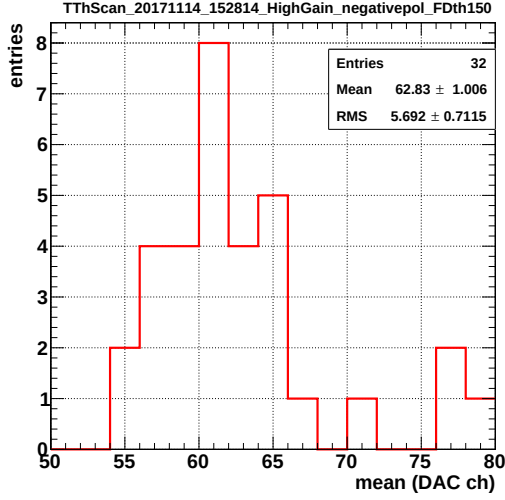
The average gain is reported in Eq. 5.6 and 5.7, where the systematic error is introduced by the uncertainty over the capacitance C_{test} .

$$\langle G \rangle_{\text{high gain}} = [20.62 \pm 0.41 \text{ (stat)} \pm 1.03 \text{ (syst)}] \frac{mV}{fC} \quad (5.6)$$

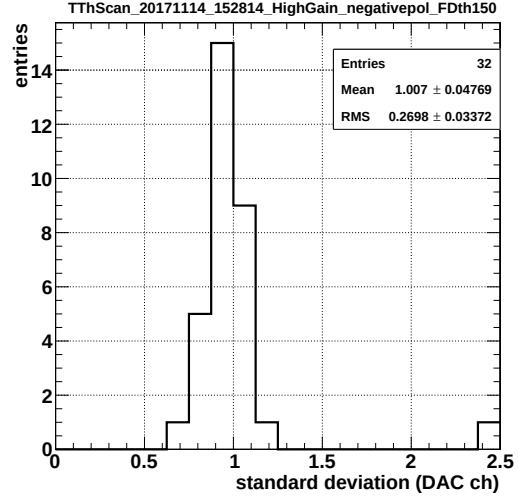
$$\langle G \rangle_{\text{low gain}} = [7.082 \pm 0.139 \text{ (stat)} \pm 0.36 \text{ (syst)}] \frac{mV}{fC} \quad (5.7)$$

The non-uniformity of the gain values has to be included in the systematic error, since the test board contains one condensator per channel. The gain values, in

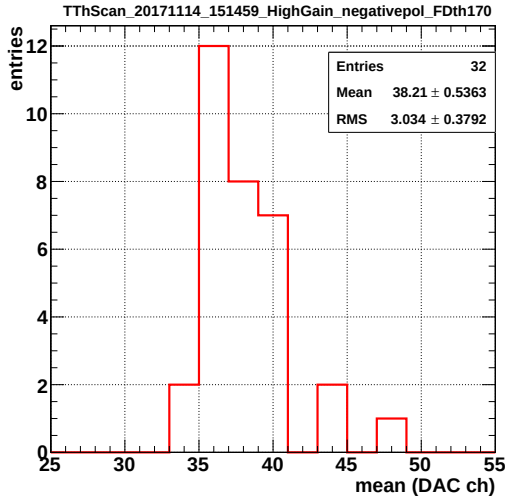
both high and low gain mode, are lower than expected (50 mV/fC and 10 mV/fC respectively, see Table 5.1) and the cause is under investigation.



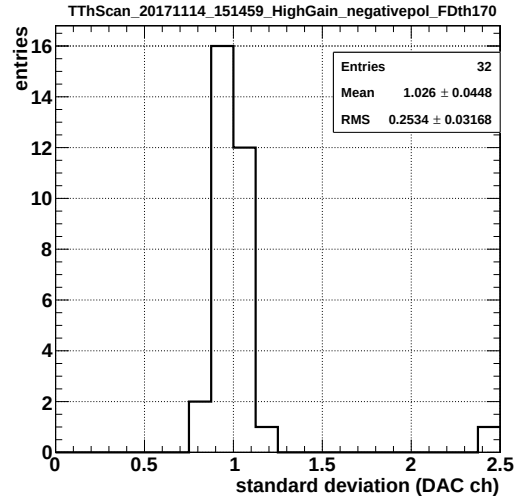
(a) Th = 150 - Mean



(b) Th = 150 - Standard Deviation

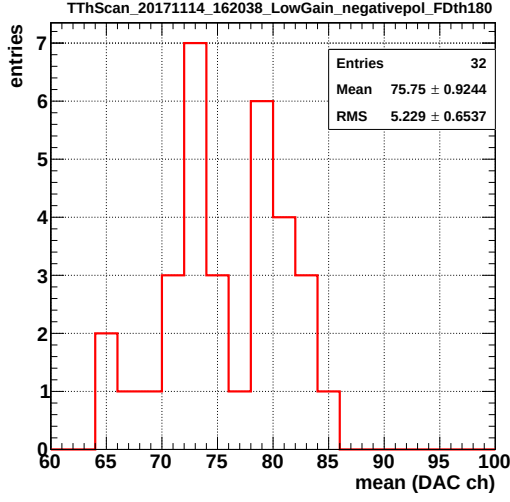


(c) Th = 170 - Mean

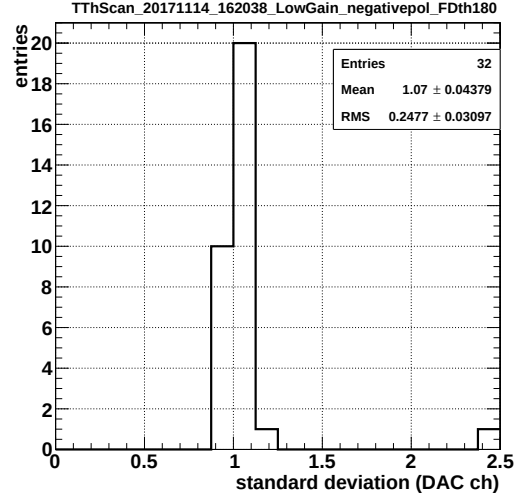


(d) Th = 170 - Standard Deviation

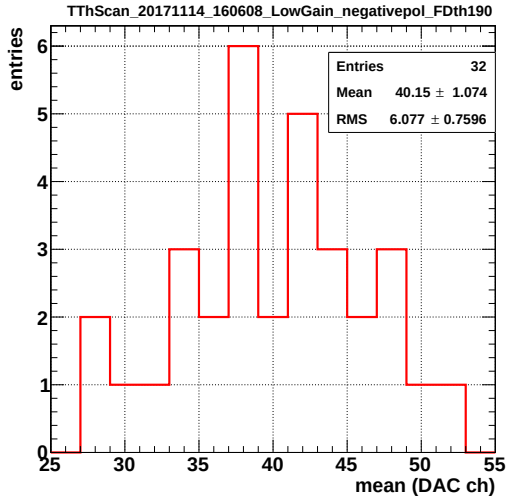
Figure 5.6: Distribution of mean and standard deviation of sigmoid fits for all 32 FATIC channels, for different values of Fast Comparator threshold. The CSA was operated in high gain mode while the Arming Comparator was disabled.



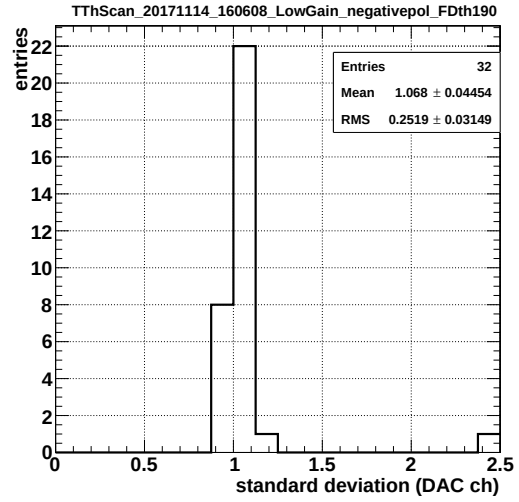
(a) Th = 180 - Mean



(b) Th = 180 - Standard Deviation



(c) Th = 190 - Mean



(d) Th = 190 - Standard Deviation

Figure 5.7: Distribution of mean and standard deviation of sigmoid fits for all 32 FATIC channels, for different values of Fast Comparator threshold. The CSA was operated in low gain mode while the Arming Comparator was disabled.

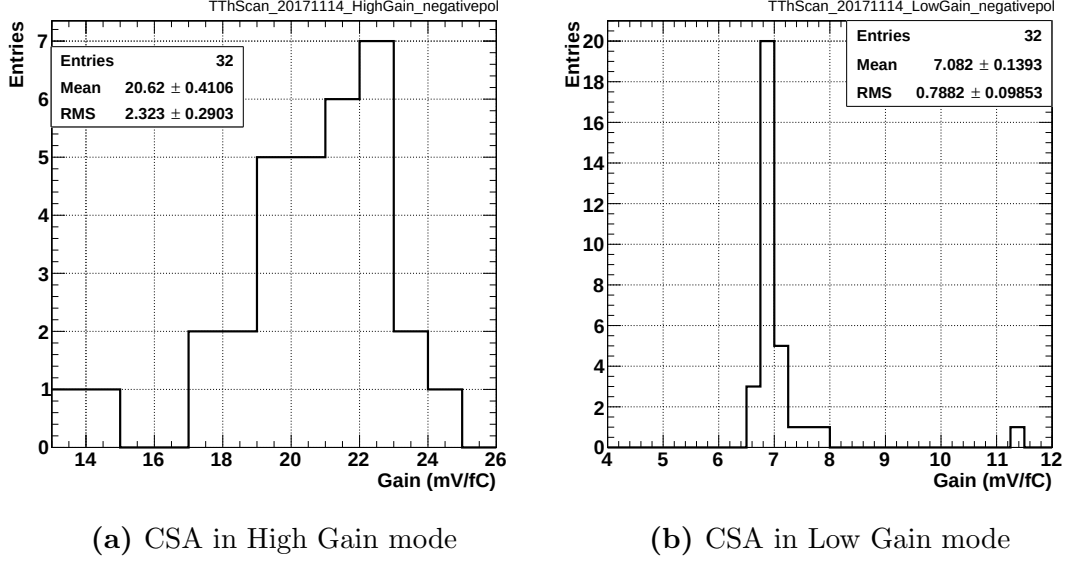


Figure 5.8: CSA gain measured for all channels.

In order to evaluate the CSA linearity in high gain mode, different sigmoid curves were measured varying the FC threshold in the DAC ranges $[0; 220]$ (negative polarity) and $[220; 255]$ (positive polarity). Figure 5.9 shows the output response of channel 15 as a function of the injected charge. The uncertainty on the determination of the injected charge is 25% (errors not shown). It is clear that the dynamic range of positive polarity signals is limited by the asymmetric position of the baseline.

So far the CSA performance was tested reading the digital signals from the timing branch. Subsequently, the charge branch was used to investigate the effect of the shaper circuit on the noise. Enabling the *Arming Comparator* and setting a low threshold ($\sim 50\text{mV}$) on the *Fast Comparator*, the sigmoid-curve measurement was repeated for all channels. Figure 5.10 shows the distribution of μ and σ : it is noticeable that the thresholds are mismatched also for the AC. As for the FC, a threshold-equalization 6-bit DAC per channel allows to correct the mismatch. In this case, the average standard deviation (i.e. the ENC) is

$$\langle \sigma_{\text{charge branch}} \rangle \simeq 0.84 \text{ DAC unit} \simeq 0.084 \text{ fC} \simeq 525 e^- \quad (5.8)$$

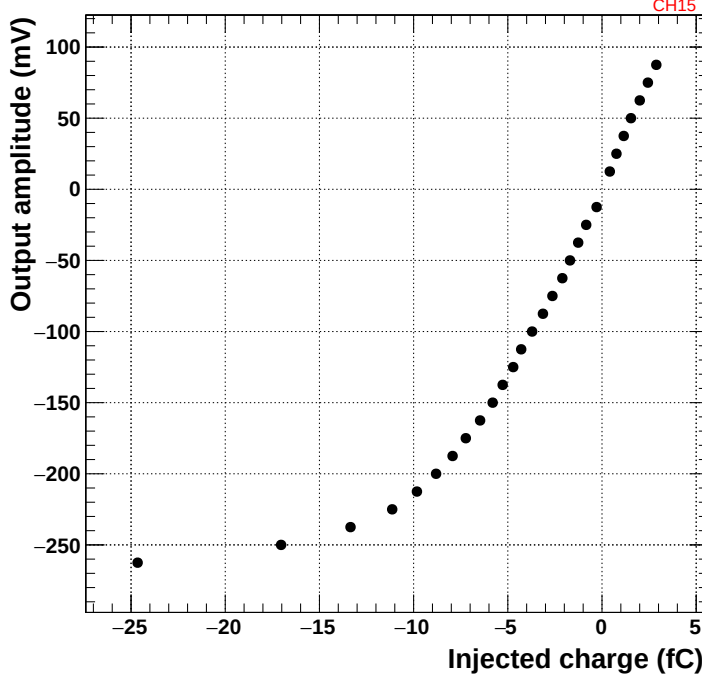


Figure 5.9: CSA transfer characteristics measured in high gain mode.

and the noise reduction can be estimated as follows:

$$\%ENC_{reduction} = \frac{\langle \sigma_{timing\ branch} \rangle - \langle \sigma_{charge\ branch} \rangle}{\langle \sigma_{timing\ branch} \rangle} \simeq 20\% \quad (5.9)$$

5.3.3 Fast Comparator: time walk and jitter

Timing fluctuations caused by noise and/or statistical fluctuations in the sensor (intrinsic noise) can affect the performances of the TDC. Two identical signals can in fact be triggered at different points and the time variation depends on the signal-to-noise ratio and on the TDC resolution. This effect is called *jitter*. Furthermore, the time of threshold crossing depends on the pulse amplitude and its rise time. Indeed, larger signals have a greater slope and cross the threshold earlier than smaller ones, as illustrated in Figure 5.11a. The signal rise time, in the FATIC timing branch, is limited by the CSA peaking time (7.3 ns, see Table 5.1). The variance of the delay between identical signals is a measure of the *jitter* effect,

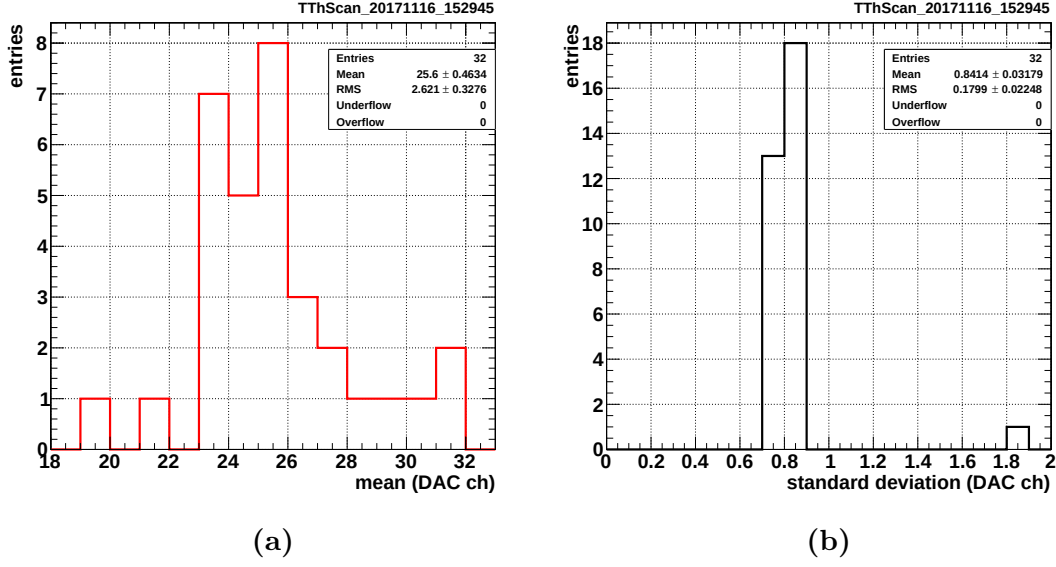


Figure 5.10: Distribution of mean and σ of sigmoid fits for all 32 FATIC channels. The CSA was operated in high gain mode, the FC threshold was set at 200 DAC units, the AC was enabled with threshold 40 DAC units.

while the variation in time caused by signal amplitude variation is called *time walk*. The measurement of timing fluctuations on the FATIC was performed using the LEMO I/Os on the MOSAIC board. The board was programmed to read the input trigger from the clock of the board and the fast-OR signal for the FATIC chip. One single channel of the FATIC was tested with a sequence of pulses and the delay time between the output fast-OR signal and the input trigger was measured on the oscilloscope. The measured delay time was averaged on a large number of pulses (10^3), from which the maximum delay was subtracted, depending only on the cable lengths and on the paths inside the MOSAIC board. The plot in Figure 5.12a reports the time walk as a function of the injected charge, for different values of the FC threshold. The uncertainty on the determination of the injected charge is 25% (tolerance of the capacitors, not shown as errors). The standard deviation of the measured delay time is the jitter and it is reported in Figure 5.12b. Jitter can also be evaluated as the ratio between the noise amplitude (σ_n) and the slew rate (dV/dt) near the threshold level, as shown in Figure 5.11b. It is therefore clear that jitter is expected to asymptotically decrease as the injected charge increases,

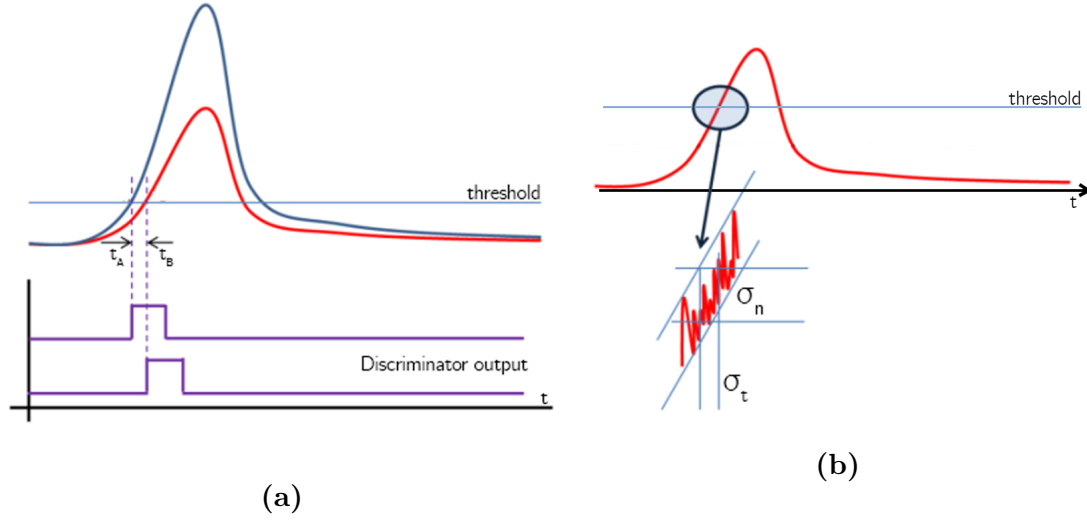


Figure 5.11: Time walk $\Delta t = |t_B - t_A|$ and jitter σ_t

keeping the threshold constant. From data it is noticeable that the maximum measured time walk is compatible with the nominal CSA peaking time (7.3 ns), and the minimum jitter (that corresponds to the best s/n ratio) is ~ 100 ps, which is the TDC resolution. However, the values of jitter at low input charges are different with respect to simulation: as reported in Table 5.1, the designed and simulated jitter with 1 fC input charge is 300 ps, while the same value was measured with 3 fC input charge. This difference is attributable to the discrepancy between simulated (50 mV/fC) and measured (~ 20 mV/fC) gain. Therefore, if the gain is only 20 mV/fC, the required 50 mV as input of the discriminator is only reached with a 2.5 fC pulse instead of the foreseen 1 fC. It is clear that the FATIC chip reaches better timing performances with higher injected charge. Low jitter (100 ps) is reached at $10\text{ fC} \simeq 6 \cdot 10^4 e^-$ injected charge, which corresponds to a gain that exceeds the value of 10^4 expected from the FTM detector.

5.3.4 TDC: linearity

To characterize the Time-to-Digital Converter, the test setup was modified by adding a scintillator under exposure of a ^{90}Sr source. The experimental procedures used in this test are explained in detail in [54]. The features of the TDC are

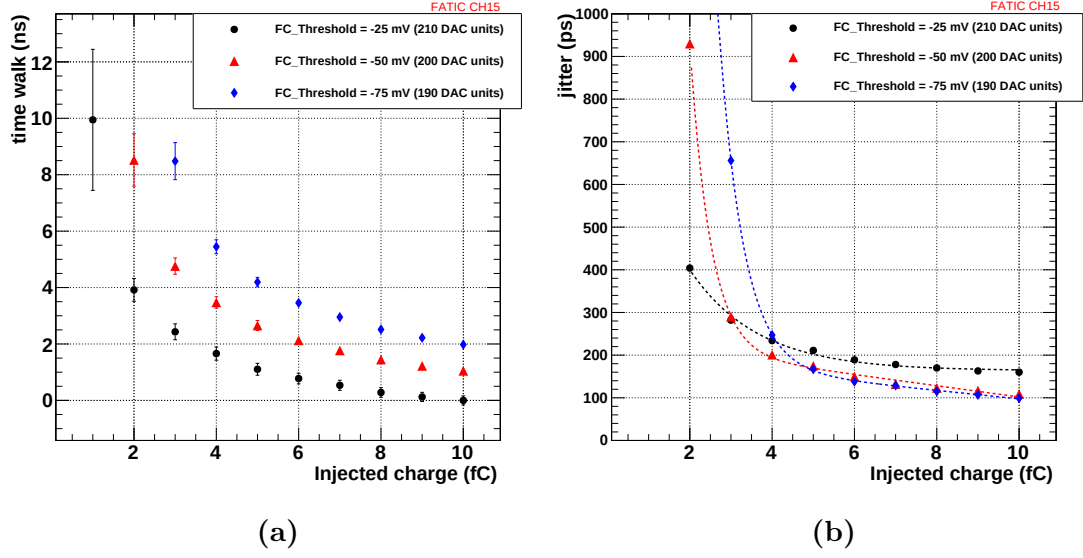


Figure 5.12: Time walk and jitter as a function of the injected charge in channel 15. CSA in High Gain mode, Arming Comparator disabled.

summarized in Table 5.1. The collection of a large number of random distributed events allows to measure the differential and integral non-linearity errors of the 5-bit fine counter. The digital output range can be divided in $2^5 = 32$ bins. In an ideal converter the transfer function is linear and the width of every bin is exactly equal to the LSB quantization step. The Differential Non-Linearity (DNL) error indicates the difference in width of each bin with respect to the mean width, and it is calculated as follows:

$$DNL_i = \frac{N_i - N_t}{N_t} \quad (5.10)$$

where N_i is the actual number of occurrences in the i -th bin and N_t is the theoretical number of occurrences, which is expected to be the same for all bins. The Integral Non-Linearity (INL) error is described as the deviation, in LSB units, of the actual transfer function from a straight line and it is calculated by the following equation:

$$INL_i = \sum_{i=1}^j \frac{DNL_i}{M} \quad (5.11)$$

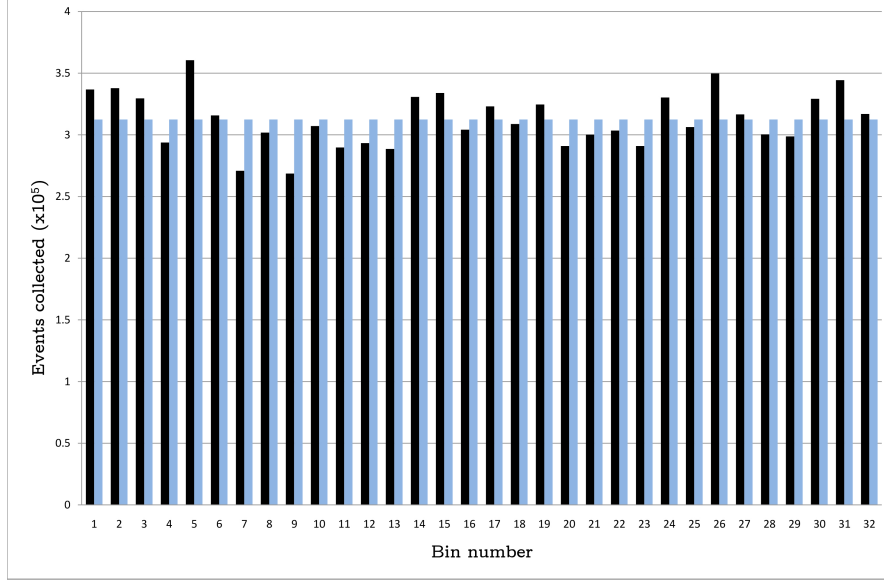


Figure 5.13: Histogram of events collected from the ^{90}Sr source. Courtesy of G. De Robertis

where M is the total number of bins. The data collected with the ^{90}Sr source are reported in the histogram in Figure 5.13, each bar representing the number of collected (black) and expected (light blue) events in the i -th bin. The histogram appears to be regular. The values calculated for DNL and INL are plotted in Figure 5.14: the errors are less than 1 LSB and the plots are equally distributed around zero. Therefore it is possible to conclude that the TDC is very uniform over the whole range.

5.4 Conclusions

The first version of the FATIC chip was characterized in order to evaluate his performances and to prepare the first tests on the FTM prototype. The results are summarized in Table 5.2: the gain is about 20 mV/fc in *High Gain* mode and 7 mV/fc in *Low Gain* mode; the ENC was evaluated as the σ parameter of the sigmoid response curve (5.3) and on average it is about 0.1 fC (625 e^-), reduced to 0.08 fC by the shaper, while 300 ps jitter is reached with a 3 fC input charge. The most important aspect to investigate is the difference between the expected

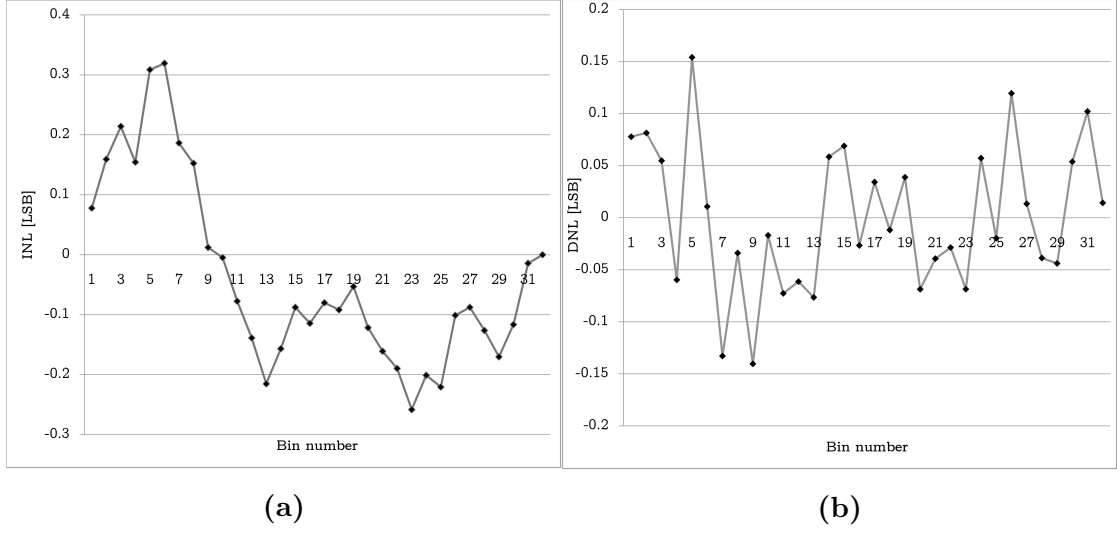


Figure 5.14: DNL (left) and INL (right) errors calculated from the data taken with the random input signal, generated with a ^{90}Sr source. Courtesy of G. De Robertis

and the measured gain of the CSA: a higher gain is needed to improve the signal-to-noise ratio for small signals. Moreover, it is clear that it is mandatory to have a test circuit internal to the chip, in order to evaluate and correct the threshold mismatch. The introduction of these upgrades is planned for the second version of the FATIC chip.

Table 5.2: Summary of the FATIC characterization results

Time jitter	300ps@3fC input charge	
Gain	High	$\simeq 20 \text{ mV/fC}$
	Low	$\simeq 7.1 \text{ mV/fC}$
ENC	Fast Comparator	$0.1043 \text{ fC} \simeq 652e^-$
	Arming Comparator	$0.084 \text{ fC} \simeq 525e^-$

Conclusions

The work presented in this thesis concentrated on the development of the Fast Timing Micro-pattern gaseous detector (FTM), together with the tests of its dedicated electronics.

The time resolution of MPGDs is mostly determined by the statistical fluctuations on the production of primary electron-ion pairs and it is limited to few ns. The FTM was developed to overcome this limit: the basic idea to improve the time resolution in a spark-protected MPGD is the segmentation of the drift gap and the use of fully resistive WELL layers.

As discussed in Chapter 2, the existing FTM prototypes had different limitations and construction problems and the FTM v.4 was designed in order to overcome these problems and confirm (and extend) the results obtained with the very first FTM prototype: the new prototype has four 50 μm -thick kapton amplification structures similar to the ones used in the first prototype; on the other hand, several upgrades were implemented on the FTM v.4, such as the completely modular design, the forced gasflow through all detection layers, the front-end electronics mounted as close as possible to the readout strips, the use of high speed connectors with rugged grounding.

The new FTM was assembled during the thesis at CERN and tested with x-rays in Bari. The experimental setup was validated with a Single-GEM detector used as a benchmark. An experimental procedure for the characterization of MPGD detectors has been established. The tests showed the limitations of using x-rays for thin-drift-gap resistive detectors and the setting up of a UV laser facility has been proposed for future tests.

On the other hand, the gain of a single-GEM detector has been measured with

high precision and the same procedure can be exploited to test GEM detectors with different geometries, e.g. thick-GEM detectors, in order to explore alternative options for the FTM amplification layers for future prototypes.

A dedicated electronics for the acquisition of small signals with good time resolution has been developed in Bari. The first version of the FAsT Timing Integrated Circuit (FATIC) has been characterized and the comparison between its performances and the FTM requirements have led to improvements for the design of the second version of the chip.

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List of Acronyms

AC	<i>Arming Comparator</i>
ADC	Analog to Digital Converter
ALICE	A Large Ion Collider Experiment
ASIC	Application Specific Integrated Circuit
CERN	European Organization for Nuclear Research
COMPASS	Common Muon and Proton Apparatus for Structure and Spectroscopy
CSA	Charge Sensitive Amplifier
DAC	Digital to Analog Converter
DAQ	Data Acquisition
DNL	Differential Non-Linearity
DLC	Diamond-Like Carbon
ENC	Equivalent Noise Charge
FATIC	FAst Timing Integrated Circuit
FC	<i>Fast Comparator</i>
FCCL	Flexible Copper Clad Laminate
FPGA	Field Programmable Gate Array

FTM	Fast Timing Micro-pattern gaseous detector
GEM	Gas Electron Multiplier
HEP	High Energy Physics
INL	Integral Non-Linearity
LHC	Large Hadron Collider
LSB	Least Significant Bit
LVDS	Low Voltage Differential Signals
Micromegas	MICRO-MESh GASEous Structure
MIP	Minimum Ionizing Particle
MOSAIC	MODular System for Acquisition, Interface and Control
MPGD	Micro Pattern Gaseous Detector
MRPC	Multigap Resistive Plate Chamber
MSGC	Micro-Strip Gas Counter
MWPC	Multi-Wire Proportional Chamber
NTP	Normal Temperature and Pressure
PCB	Printed Circuit Board
RPC	Resistive Plate Chamber
SWPC	Single-Wire Proportional Counter
TDC	Time-to-Digital Converter
TOTEM	TOTAL Elastic and diffractive cross section Measurement