Development of a tracker based on GEM optically readout

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Introduction

The high-resolution tracking of low energy release particles had a remarkable development in recent years and will give a crucial contribution in different sectors, from medical applications to those in dark matter search.

Thanks to their characteristics (high space and time resolution, low material budget, large volumes, low costs) the gas detectors have shown to be ideal candidates for this type of trackers. In particular, a very promising technique regards the optical reading of the light produced by the de-excitation of gas molecules during the processes of electron multiplication. This type of detector has been made possible thanks to the great progresses achieved in last years in the performance in micro pattern gas detector and in the evolution of the CMOS technology which led to the production of sensors able of offering high sensitivity and granularity combined with a very low noise level. In this thesis I studied the performance of a two prototypes where the light is produced through the multiplication of electrons in a triple GEM structure and acquired by a camera equipped with CMOS sensor with 4 Mega Pixels.

The use of high light yield $\text{HeCF}_4$ gas mixture allowed to reveal, for the first time with this technique, the tracks of minimum ionizing particles. The performance of this detector were measured and optimized in laboratory and tested on an electron beam at the Beam Test Facility of the National Laboratories of Frascati.

The thesis is subdivided into five parts:

**Chapter 1**: Description of all the working principles of particle gas detectors with more detail on processes occurring in GEM gas electron multiplies and in gas scintillation;

**Chapter 2**: Description in general terms on photo-sensors based on CMOS technology;

**Chapter 3**: Detailed description of the main features of ORANGE prototypes. The optical system was studied and optimized to efficiently collect the produced light;
Chapter 4: Results of the measurements performed in laboratory by means of cosmic ray muons. The detector transparency to electrons was studied and maximized, and the light yield behaviour was measured. The CMOS sensitivity to the light was verified and its response calibrated. Several gas mixtures were tested and their characteristics simulated;

Chapter 5: Description and analysis of tests performed on electron beams. The detector light yield and electronic gain were measured as a function of GEM high voltage supplied and beam energy. A simple algorithm was developed to study the tracking capability of the device.
Chapter 1

Gas Electron Multipliers

Physical phenomena that occur in this type of devices involve the electromagnetic interactions of particles with matter. In the case of a gas detector, the Coulomb interaction is the dominant process that causes the ionization and the excitation of the molecules of the medium. The other electromagnetic interactions (Bremsstrahlung, Cherenkov radiation,..) contribute little to the total released energy. The main processes occurring in gas detectors after the crossing of charged particles are summarized in this chapter.

1.1 Ionization in matter

A charged fast particle passing in a medium delivers energy to atoms and molecules. The incident particle, which has charge $z e$, mass $m$ and velocity $v$, travels in the medium and sees the electrons move with velocity $-v$, in its reference frame.

Considering an electron at a distance $b$ from the particle trajectory, see fig. 1.1 the transferred momentum will be $p_e = \int e \cdot \vec{E}$ and, since the longitudinal component is canceled for symmetry, the transverse component remains:

$$p_e = \int e \cdot E_\perp dt = \frac{e}{v} \int E_\perp dx. \quad (1.1)$$

At this momentum it corresponds, in non-relativistic approximation, an energy transferred to the electron of medium:

$$T_e = \frac{p_e^2}{2m_e} = \left(\frac{ze^2}{4\pi\epsilon_0 b}\right)^2 \frac{2}{m_e v^2} = 2m_e c^2 \frac{z^2}{\beta^2 b^2}, \quad (1.2)$$

introducing the classical radius of electron $r_e = e^2/4\pi\epsilon_0 m_e c^2 = 2.8 \text{ fm}$ and $\beta = v/c$. 


The probability $dw$ that one particle undergoes a collision in a unit path between $b$ and $b + db$ is $dw = 2\pi bdb$ and, using the formula, we have:

$$\frac{dw}{dT_e} = 2\pi r_e^2 m_e c^2 n_e \frac{z^2}{\beta^2 T_e^2}$$  \hspace{1cm} (1.3)$$

For the total energy transferred in a path $dx$, we must multiply the energy transferred per collision by the corresponding cylindrical ring volume, $2\pi dbdx$, and by the electron density $n_e$:

$$\frac{d^2 E}{dx db} = -4\pi n_e m_e c^2 z^2 r_e^2 \frac{\beta^2}{b}$$  \hspace{1cm} (1.4)$$

that integrated on $b$ between $b_m$ and $b_M$ becomes:

$$- \frac{dE}{dx} = 4\pi n_e r_e^2 m_e c^2 z^2 \frac{\beta^2}{\tilde{b}} \int_{b_m}^{b_M} db \frac{b}{b}$$  \hspace{1cm} (1.5)$$

where $b_m$, for the indetermination principle, represents best measurement of the position for a variation of the pulse $p_e$, $b_m = \frac{\hbar}{p_e} = \frac{\hbar}{m_e c \gamma}$, and $b_M$ taking in to account that the collision time must to be lower than the revolution time of electron, $b_M \simeq \frac{\omega_e}{\omega_e} = \frac{b c \gamma}{\omega_e}$.

Inserting this value in the equation $(1.5)$ we obtain the Bohr formula:

$$- \frac{dE}{dx} = 4\pi n_e r_e^2 m_e c^2 z^2 \ln \left( \frac{m_e c^2 \beta^2 \gamma^2}{\hbar \omega_e} \right) = 4\pi \frac{N_A Z \rho}{A} \frac{n_e \omega_e}{A} \frac{r_e^2 m_e c^2 z^2}{\beta^2} \ln \left( \frac{m_e c^2 \beta^2 \gamma^2}{\hbar \omega_e} \right)$$  \hspace{1cm} (1.6)$$

where $n_e = \rho \frac{N_A Z}{A}$, $N_A$ is the Avogadro number, $Z$ the atomic number, $A$ the atomic weight and $\rho$ the electron density in the matter traversed.
If the incident particles are the electrons, the Bethe e Block formula must be changed taking into account the identity between projectile and target. As a result of elastic collision with the nucleus, the acceleration that a particle undergoes when it is deflected causes the emission of electromagnetic radiation and the acceleration will be as greater as smaller the particle mass is. To the Bethe and Block formula another term that takes in to account the energy losses due to radiation would add:

\[
\left(-\frac{dE}{dx}\right)_{\text{rad}} \simeq \frac{E}{X_0} \simeq 4r_0^2 \alpha \frac{N_A Z^2 \rho}{A} \ln(183Z^{-1/3})E
\]

(1.7)

Since these losses are linear in \( E \), when \( E \) increases the radiative contribution will be greater than the ionization, which tends to become constant.

### 1.1.1 Gaseous medium

A charged particle that traverses a layer of a gas can release a track of ionization along its trajectory, producing ion-electron pairs. In this case it is possible to write the Bhete e Bloch formula as:

\[
-\frac{dE}{dx} = k \frac{Zz}{A} \rho \beta^2 \left( \ln \frac{2m_e c^2 \beta^2 \gamma^2 E_m}{I^2} - 2 \beta^2 \right), \quad k = \frac{2\pi N_A z^2 e^4}{m_e c^2}.
\]

(1.8)

In this equation \( m_e c^2 \) is the rest energy of the electron, \( z \) the charge of the travelling particle, \( \beta \) the velocity of the travelling particle in term of the light velocity \( c \), \( \gamma^2 = 1/(1 - \beta^2) \), \( I \) is the ionization potential of the medium (where \( I = I_0 \cdot Z \) and \( I_0 = 11.6eV \) and \( E_m \) is the maximum of the energy lost in a single collision:

\[
E_m = \frac{2m_e c^2 \beta^2}{1 - \beta^2}.
\]

(1.9)

From this formula we can say that:

- neglecting the logarithmic dependence on \( I \), the energy loss does not depend on the different material properties;
- for small \( \beta \), the energy loss goes as \( 1/\beta^2 \), then moves to the minimum and increases logarithmically when \( \beta \gamma = \frac{p}{M c} > 3 \).
- the value of \( \beta \gamma \), that corresponds to the minimum, depends weakly on \( I \) (see fig. [1.2]).
- the energy loss is proportional to the square of the particle charge;
- the mass of the incident particle comes into play only by \( \beta \gamma = \frac{p}{M c} \).
Figure 1.2: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. [7]
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The Bhete Block formula takes into account the energy losses in all energetic processes: from simple atomic excitation (big impact parameter) to the transfer of energy to the electrons, δ rays (small impact parameter). The total amount of energy loss can be described by:

\[ W < N_I > = L \frac{dE}{dx} \]  

(1.10)

where \( W \) is the average energy that is necessary to create a free electron \(^3\), \( < N_I > \) is the average number of ionized electrons along the trajectory of length \( L \).

The interactions with the atoms of the gas are random and are characterized by a mean free flight path \( \lambda \) which is given by the ratio \(^4\):

\[ \lambda = \frac{1}{(\rho_0\sigma)} \]  

(1.11)

where \( \rho_0 \) is density of target and \( \sigma \) the ionization cross-section. The number of interactions that can occur in a length \( L \) has a Poisson distribution, with mean equal to \( n = L/l \):

\[ P(n, k) = \frac{(n)^k}{k!} e^{-n}. \]  

(1.12)

1.2 Presence of the electric field

Applying an electric field on gas, the ionized particles, electrons and ions, move on the field lines and, along these, they are scattered by the gas molecules. If we consider a particle with charge \( q \) and mass \( m \), in a medium with an electric field \( E \), we obtain \(^{16}\):

\[ m \left( \frac{dv}{dt} \right) = qE - kv \]  

(1.13)

where \(-kv\) represents the friction force proportional to the particle velocity. The constant \( k \) can be written as \( k = \frac{m}{\tau} \), in which \( \tau \) defines the average time between two collisions (Townsend). When \( t > \tau \) the term \(-kv\) can be neglected and the equation has a constant solution:

\[ v = \frac{q\tau}{m} E = \mu E, \quad \frac{dv}{dt} = 0 \]  

(1.14)

With \( \mu \) as defined the charge mobility inversely proportional to the particle mass and directly proportional to \( \tau \) and to the charge of particle.
1.2.1 Electrons

The emitted electrons, because of their light mass, scatter isotropically and, after collisions, forget any preferential direction: their velocity will have a component with average value equal to zero in all directions, to this the velocity towards the electric field $E$ is added.

Staring by the formula 1.14 (on left), that defines the average drift velocity and, writing $1/\tau = u/\lambda = u\rho \sigma$, we have:

$$v = \left( \frac{e}{m\sigma u} \right) \frac{E}{\rho}. \quad (1.15)$$

In this equation the term $E/\rho$ is the reduced field, $u$ is the instantaneous velocity of the electrons and $\sigma$ is the cross section between the electron and the gas molecule that depends by the electron energy $\epsilon \rightarrow \sigma = \sigma(\epsilon)$.

The presence of the nuclei of the medium allows the particles, that crossing it, to collide with them through coulombian elastic collisions. In each collision the direction of motion changes and, after many interactions, the new direction will be the result of many small deflections.

The cross section that describes the single collision is given by the Rutherford

$$\frac{d\sigma}{d\Omega} = z^2 Z'^2 r_e^2 mc^2 \frac{1}{p^3 4\sin^4 (\theta/2)} \quad (1.16)$$

but, in the case of a high number of collision, the process is explained with the multiple scattering. In this last case, the exit angle $\theta$ of the particle will have a Gaussian distribution

$$P(\theta) = \frac{2\theta}{<\theta^2>} e^{-\frac{2\theta^2}{<\theta^2>} d\theta} \quad (1.17)$$

with fluctuation equal to

$$\theta_{rms} = \sqrt{<\theta^2>} = \frac{21MeV/c}{p\beta c} \sqrt{\frac{x}{X_0}} \quad (1.18)$$

in which $p$ is the particle momentum, $x$ is the traversed thick and $X_0$ is the radiation length. In both the direction orthogonal to the particle velocity becomes:

$$P(\theta_y) d\Omega = \frac{1}{\sqrt{2\pi} <\theta_y^2>} e^{-\frac{s_y^2}{2<\theta_y^2>} d\theta_y} \quad (1.19)$$

with the corresponding fluctuation:

$$\theta_{y, rms} = \sqrt{0.5 <\theta^2>} = \frac{13.6MeV/c}{p\beta c} \sqrt{\frac{x}{X_0}}. \quad (1.20)$$
1.2.2 Ions

The drift of ions differs from the one of electrons because of their larger mass. Good fraction of the energy is lost in the collision and momentum of the ions is not randomized. The ions drift velocity is:

\[ v^+ = \frac{\mu^+ E}{\rho} \]  

where \( \mu \) is the mobility of the ions, which is specific for each gas, and \( E/\rho \) is the reduced field. The mobility and the diffusion coefficient are linked by the Nernst-Towsend formula (or Einstein formula) by:

\[ \frac{D}{\mu} = \frac{kT}{e} \]  

which is, in the ions case, a constant. This characteristic is given by the constant average energy of the ions in the gas.

For a gas mixture the mobility \( \mu^+_i \) of the ion \( G^+_i \) can be evaluated by the Blanc’s law:

\[ \frac{1}{\mu^+_i} = \sum_{j=1}^{n} p_j \frac{\mu^+_j}{\mu^+_{ij}} \]  

where \( p_j \) is the gas concentration \( j \) in a volume and \( \mu^+_{ij} \) is the mobility of the ion \( G^+_i \) in the gas \( G_j \).

When the migrating ions collide with molecules that have a ionization potential smaller than the energy available in the ion, there is the possibility that a charge-exchange process take place, which neutralizes the ion and creates a new ion. This process happens with cross-sections that are of a similar order of magnitude to other ion-molecule scattering cross-sections. Therefore the rate of ions transformation through charge transfer is correspondingly high and proportional to the concentration of the molecules to be ionized.

1.2.3 Diffusion

When the drifting electrons are scattered on a gas molecules, their velocities change from the average. In the simplest case, the deviations are the same in all directions and if the process begins with a point-like cloud of electrons, at a time \( t = 0 \) in the origin of the system along the direction \( z \), after some time \( t \), the cloud will assume a Gaussian density distribution:

\[ n = \left( \frac{1}{\sqrt{4\pi Dt}} \right)^3 e^{-\frac{r^2}{4Dt}} \]  

(1.24)
where \( r^2 = x^2 + y^2 + (z - vt)^2 \) and \( D \) is the diffusion constant. By the microscopic interpretation, starting from the equation 1.22 and writing the average thermal energy as \( \epsilon = 3/2kT \), we can write \( D \) as:

\[
D = \frac{2}{3} \frac{\epsilon}{m} \tau \tag{1.25}
\]

and remembering that \( \mu = \frac{e}{m} \tau \), we can find the electron energy measuring the ratio \( D/\mu \):

\[
\epsilon = \frac{3}{2} \frac{D}{\mu} \tag{1.26}
\]

The energy defines the diffusion width \( \sigma_x \) of an electron cloud which, after starting point-like, has travelled over distance \( L \):

\[
\sigma_x^2 = 2Dt = \frac{2DL}{\mu E} = \frac{4\epsilon L}{3eE}. \tag{1.27}
\]

Experimentally the value of the electron diffusion along the electric field can be quite different from that in the perpendicular direction. We know that the diffusion of the drifting ions is non-isotropic: when the ions collide with the gas molecules, they retain the direction of the motion along the electric field because the partners of the collision is similar. Results that the diffusion is larger in the drift direction.

For the electrons, restricting the study to energy loss by elastic collisions, we consider the mobility. The mobility of electron assumes different value along the edge and in the center of the travelling cloud. This change of mobility inside the cloud corresponds to a change of diffusion in the longitudinal direction; the diffusion in the perpendicular direction also change. Introducing the two diffusion coefficients related to longitudinal \( (D_L) \) and perpendicular \( (D_T) \) diffusions, the distribution density in the anisotropic case becomes \[16\]:

\[
n = \frac{1}{\sqrt{4\pi D_L t}} \left( \frac{1}{\sqrt{4\pi D_T t}} \right)^2 e^{-\left[ \frac{x^2 + y^2}{4D_T t} - \frac{(z - vt)^2}{4D_L t} \right]} \tag{1.28}
\]

### 1.2.4 High electric fields

The increase of the electric field above some keV/cm leads to an increasing number of ionized electrons that have the energy to produce inelastic phenomena when collide with molecules: ionizations and excitations.

When the electron emitted has an energy that reaches the first ionization potential of the gas molecule, it may create an electron ion pair and it can lead to multiplication process. Two different types of ionization can take place: primary and secondary \[4\], fig. 1.3.
The primary ionization is one in which, to the passage of the fast particle, one or more electrons are ejected from the molecules. The secondary electrons are usually created in the immediate neighborhood of the primary encounter and, together with the primary electrons, form a structure called clusters of one or several electrons.

The excitations, that often concerns vibrational and rotational levels of molecules, can also involves the energetic levels exciting them and then emitting a photon, returning in the ground state. Unlike the ions and the electrons, the photons produced are not influenced by the electric field. They can interact with the gas molecules by the photoelectric interaction that it is possible only when the photons have sufficient energy to overcome the binding energy to remove the electron from the atom. The typical photon energy is $E_\gamma \ll m_e c^2$, the process can be as

$$\gamma + A \rightarrow e^- + A^+ \quad (1.29)$$

the corresponding cross-section is

$$\sigma_{p.e.} \propto Z^5 \frac{1}{E_\gamma} \quad (1.30)$$
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and it depends strongly by the atomic number of the material, \[7\].

1.3 Gas electron multiplication

The Gas Electron Multiplier, GEM \[17\], is a micro-pattern gas detector that can be used for the high resolution particle tracking. With this device the electrons, which are produced in a gas mixture by a ionizing particles, are multiplied within the GEM channels where a high electric field is present.

1.3.1 Single GEM

The standard GEM is a kapton foil with a thickness of about 50 \(\mu\text{m}\), clad on each side with a thin copper layer (5 \(\mu\text{m}\)) and perforated with holes with a high surface density. The holes have a bi-conical shape with a diameter ranging from 70 \(\mu\text{m}\) to 150 \(\mu\text{m}\). In fig. 1.4 it is possible to see a foil magnification and, in fig. 1.5 the hole cross-section, as seen at electron microscope.

![GEM foil under electron microscope](image)

Figure 1.4: GEM foil as seen under at the electron microscope, \[5\].

By applying a voltage difference of about 500 V between the two copper sides, an electric field of 100 kV/cm is produced within the holes, the channel field \(E_c\). When a charged particle passes through the gas, ionizes molecules that generate primary electrons. An external electric field, fig. 1.6 drift field \(E_d\), can bring the primary electrons through the GEM and the high field
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Figure 1.5: GEM hole cross-section as seen at electron microscope. [5]

Figure 1.6: Schematic view of the single sheet GEM.
inside the holes induces an avalanche process. In transfer gap, a transfer electric field $E_t$ extract secondary electrons, see fig. 1.7.

1.3.2 Single GEM electron transparency

The electron transparency represents the probability that an electron, produced in the drift zone, arrives in the transfer area crossing a channel of the GEM foil.

Because of the diffusion effect and the defocused field lines, some electrons can collide with the upper GEM electrode, as we can see in fig. 1.8. The ratio between the number the electrons entering in the channel and the number of electrons above the GEM is defined as the collection efficiency: $\epsilon_{coll}$.

Some electrons are lost on the kapton inside the GEM while others can hit the lower side of the GEM foil due to the poor extraction capability of the electric field below the GEM. The ratio between the number of electrons extracted and the number of electrons entering in the channel is the extraction efficiency: $\epsilon_{extr}$.

The electron transparency is very important for the particle detection: it is a decisive parameter for the energy resolution and directly affects the detection performance. It is defined as

$$T = \epsilon_{coll} \cdot \epsilon_{extr}.$$  \hspace{1cm} (1.31)

Figure 1.9 shows the dependence of the efficiencies on the two electric fields (drift and transfer). When the electric field $E_d$ increases, a large fraction of electrons can hit the upper GEM copper side, causing the decrease
Figure 1.8: On the left, an electron hits the the upper electrode; on the right, an electron is lost inside a GEM channel, [5].

Figure 1.9: Transparency dependence on drift field, on the left, and on the transfer field, on the right, [5].

of the electron transparency. On the other hand a high electric drift field is necessary to avoid charge losses in the gas through secondary effects, as the recombination. In this figure, it is noted that the $\epsilon_{\text{coll}}^d$ and the transparency (total) decrease at high drift fields due to the defocusing effect, while with a better electron extraction capability the total transparency of the GEM increases at high transfer fields.
1.3.3 Single GEM gain

When the energies of the incident particle exceed the first ionization potential of the gas molecules, the ion-electron pair production occurs, which is the basis of the avalanche multiplication. The number of pairs produced in a $dx$ path is linearly proportional to the number of electrons:

$$\frac{dn}{dx} = \alpha(E) \cdot n$$  \hspace{1cm} (1.32)

The $\alpha(E)$ is called *first Townsend coefficient* and it is a function of the electric field. The electric field in the channel $E_c$ allows the development of the avalanche: the number of secondary created by primary electrons increases with the increase of $E_c$, but it reduces the extraction of the secondary electrons affecting the transparency.

If electronegative gases are used, the electron capture process will occur. The associated equation will be:

$$\frac{dn}{dx} = -\eta(E) \cdot n$$  \hspace{1cm} (1.33)

where $\eta(E)$ is called *attachment coefficient*.

The gain for a single electron drifting from $x_1$ to $x_2$ results from the above equations:

$$G_{\text{single}} = \exp\left(\int_{x_1}^{x_2} [\alpha(E) - \eta(E)]dx\right)$$  \hspace{1cm} (1.34)

which takes into account both the effects: if the field in the channel is sufficiently high the attachment effect can be neglected with respect to the multiplication; the drift lines are concentrated near the channel axis: due to the diffusion effect the electrons can reach the regions close to the kapton where the higher field results in higher multiplication.

The average number of secondary electrons produced per single electron entering into a hole will be indicated as intrinsic gain $G_{\text{intr}}$, while the average number of secondary electrons, extracted from the lower side of the GEM per primary electron generated above the GEM, will be indicated as *effective gain* $G$:

$$G = G_{\text{intr}} \cdot T$$  \hspace{1cm} (1.35)

Each single GEM has an effective gain which is an exponential function of the voltage applied:

$$G^{(i)} = A_k e^{\alpha_k V_{\text{gem}}^{(i)} T_{(i)}}$$  \hspace{1cm} (1.36)

$A_k$ and $\alpha_k$ being dependent on the gas mixture and $T$ depend on the field above and below the GEM.
1.3.4 Triple-GEM device

A triple-GEM detector is a device composed of 3 GEM foils that are sandwiched between two conductive planes: the cathode, which forms the drift gap above the first GEM, and the anode, which is usually used as signal readout. The drift gap is the space between the cathode and the first GEM in which the ionization of the gas molecules occurs. The regions between the GEMs are called transfer gaps while the induction gap is the gap between the last GEM and the anode, see fig. 1.10.

![Figure 1.10: Triple-GEM based detector cross-section](image)

Ionization electrons reach the first GEM by means of the drift electric field, and then, by means of two transfer electric fields, the electron clouds reach the second and the third GEM. Once the electrons cross the last GEM and reach the induction gap, they give rise to the formation of an induced current signal on the anode. This current is then amplified and shaped by the readout electronics.

In the transfer gaps, the secondary electron clouds are carried out from the first GEM and drifted towards the following one. Therefore, the electric field in the transfer gap ($E_t$) is an important parameter to be studied and optimized. A high $E_t$ is required to ensure a good extraction capability of the secondary electrons from the upper GEM in the transfer gap, but on the other side $E_t$ has to be jet low to reduce the defocusing effect, fig. 1.9.

1.3.5 Triple-GEM gain

It is possible evaluate the device behaviour by analyzing the gain, by adapting the equations found for the single GEM foil in the previous section.
For a system with three GEM sandwiched, the gain is essentially given by:

\[ G = G^{(1)} \cdot G^{(2)} \cdot G^{(3)} = A_k^3 \cdot T_1T_2T_3 \cdot e^{\alpha_k(V_1+V_2+V_3)} \]  

and results a function of the sum of the all voltage supplies, \( V_{tot} \). Thus the gain depends on the gas mixture characteristics, on the transparencies (i.e. the electric field configuration) and on the sum of voltage supplies, \( V_{tot} \).

### 1.3.6 Signal formation

In both single GEM and triple-GEM cases, as soon as the electrons enter into the induction gap, they start to induce on the electrodes a current, which stops when they are completely collected.

The time evolution of the current can be calculated by means of the Ramo theorem:

"Given any configuration of electrodes 1, ..., j, ..., n at different potentials \( V_1, ..., V_j, ..., V_n \), the current flowing into an electrode \( k \) due to a moving charge \( q \) is:

\[ I_k = -\frac{q\vec{v}(x) \times \vec{E}_k(x)}{V_k} \]  

where \( \vec{E}_k(x) \) is the electric field created by raising the electrode \( k \) to the potential \( V_k \) while keeping \( V_{j \neq k} = 0 \), [5].

If \( V_k = 1 \) V the resulting electric field is called weighting field \( \vec{E}_w^k \) and the Ramo theorem become:

\[ I_k = -q\vec{v}(x) \times \vec{E}_w^k(x) \]  

The real electric field is also constant in the gap and then the electron drift velocity is constant too.

The drifting electrons induce a constant current \( I \) during the drift process and if \( q \) is the charge collected, since

\[ \int_{\text{drifttime}} I \cdot dt = q, \]  

the shorter is the drift time the higher the value of \( I \). For this reason the induction gap has to be chosen as thin as possible. In figure 1.11 is possible to see the current induced by one electron on a pad in the last gap.

A detector based on triple-GEM permits to study the phenomena that occur during the ionization process inside the gaseous region that is traversed by a charged particle. The readout of the events can be achieved by using the signal induced by the electrons on appropriate electrodes, or collecting
Figure 1.11: Current $I$ induced on a pad by one electron drifting in the last gap as calculated with Ramo theorem, [5].

the light emitted by the de-excitation of the gas molecules through optical sensors like CCD or CMOS. In this thesis we present the results obtained using both the reading channels, paying greater attention to those obtained by the optical readout of the device.
Chapter 2

The CMOS photo-sensor

The optical readout of the light produced in the triple-GEM structure can be obtained by CMOS photo-sensor, i.e. Complementary Metal Oxide Semiconductor with a photosensitive element.

In the simplest form, to collect the light we used the CMOS Active Pixel Sensor (APS) consisting of one photodiode and three Metal Oxide Semiconductor Field Effect Transistor, or MOSFET.

This chapter describes, in a general way, the main features of this type of sensors, starting from some basics.

2.1 Diode and Photodiode

Diodes and photodiodes are generally devices based on p-n junction connected by two electrical terminals. The p-n junction is a layer between two types of doped semiconductors: n-type and p-type. Starting by a base of tetravalent crystal (as Si or Ge), through different technology, it is possible to insert, by repletion in their lattice, donor atoms with valence 5 (As, P) or acceptor atoms with valence 3 (B, Al). In the first case we have a n-type semiconductor with an excess of free negative charge, in the second case shortage of free negative charge, despite the crystal structure continues to be neutral.

When this two types of semiconductor are combined, the negative charges of the n-type tend to reach the p-type zone and the same thing occurs for the positive charges. This movement of the charges leads to the formation of a potential barrier $W$ which increases up to that carriers do not have enough energy to overcome. At the equilibrium, by a recombination process, a depletion zone was formed which will lead a charge inversion respect to the starting point, (see fig. 2.1).
Figure 2.1: Properties of an equilibrium p-n junction: on the left, p-region and n-region isolated and the relative energy bands; on the right, the junction, the space charge in the transition region $W$, the resulting electric field and the separation of energy bands.

The potential barrier can be modified through the application of an external voltage: the barrier becomes lower with a direct polarization (positive pole in the p-area) or highest with a inverse polarization (positive pole on the n-area).

On this basis, if an external voltage is applied:

- if the voltage has the same polarity of the build-in potential, the depletion zone behaves like an insulator, not allowing the passage of the current (this is the mode in which the photodiodes works);
- if the external voltage has opposite polarity than the built-in potential, the recombination takes place again generating an electrical current.

In the simplest way, then, we can say that a diode is an electronic component based on p-n junction equipped with two terminals that conducts primarily in one direction; it has low (ideally zero) resistance to the flow of current in one direction, and high (ideally infinite) resistance in the other.

The Shockley ideal diode equation provides the characteristic $I - V$ curve of an ideal diode:

$$ I = I_S \left( e^{\frac{V_D}{kT}} - 1 \right) $$

(2.1)

where $I$ is the diode current, $I_S$ the reverse bias saturation current, $V_D$ the voltage across the diode, $k$ the Boltzmann constant and $T$ the temperature [18].

A photodiode, formed by a p-n junction, uses the photogeneration process (or the photoelectric effect). The photogeneration process occurs when a
Figure 2.2: $I - V$ characteristic and shifting of the $I - V$ characteristic due to the photogenerated current, $I_{ph}$, [19].

A photon, which illuminates a semiconductor, has enough energy $h\nu$ to cause the excitation of an electron from the lower energy valence band to the higher energy conduction band: this process gives rise to the formation of mobile charge carriers (electron and holes).

The operation of a photodiode, then, relies on the separation of the photogenerated carriers by the built-in field inside the depletion region of the p-n junction. Under the influence of the built-in electric field, the photogenerated electrons will drift towards the n-side, and photogenerated holes will drift towards the p-side. The photogenerated carriers that reach the quasi-neutral region outside of the depletion layer will generate an electric current flowing from the n-side to the p-side; this current is called a photocurrent.

The generation of the photocurrent results in the shift of the $I - V$ characteristic of the photodiode, fig 2.2. Therefore, the $I - V$ characteristic of a photodiode is expressed as:

$$I_L = I_S[e^{\frac{qV}{kT}} - 1] - I_{ph},$$

in which the first term is the Scottky equation and $I_{ph}$ is the photocurrent.

Analyzing this curve, it is possible to find the three different trends that characterize the corresponding types of photodiodes: the open circuit mode, short circuit mode and the reverse bias mode, [19].

Open circuit mode, fig. 2.3(a), corresponds to a photovoltaic mode: the
Figure 2.3: (a) open circuit mode, (b) short circuit mode, (c) reverse- bias mode. [19]

terminals of the photodiode are connected with open circuit; there is no net current flowing across the photodiode, but due to the photogenerated current; a net voltage is created across the photodiode, called the open circuit voltage, $V_{OC}$. In fig. 2.2 the photodiode is operating at the point where the $I - V$ characteristic curve intersects the x-axis.

In the short circuit mode, the terminal of the photodiode is short-circuited. This allows the photogenerated current to flow in a loop as illustrated in fig. 2.3(b). In the fig. 2.2 this is represented by the point at which the $I - V$ characteristic curve intersects the y-axis. The current that flows in the loop in SC mode is also known as the short circuit, $I_{SC}$, and it has the same magnitude as $I_{ph}$.

In reverse bias mode, a reverse bias is applied across the photodiode as shown in fig. 2.3(c), therefore it works in the lower left quadrant of fig. 2.2. By applying a bias voltage, the potential difference across the p-n junction changes to $V_0 - V$, and the balance between drift and diffusion in the p-n junction also changes. This is reflected in the width of the depletion region $W$.

Operating in reverse bias we have the effect of increasing $W$ and the electric field $E$. The new depletion region creates a greater photogeneration region, while the stronger $E$ increases the drift velocity of the photogenerated carriers. In this way, the drift velocity increases in proportion with $E$ and the average time, that a drifting carrier has to reach the end of the depletion region (transit time), is reduced: the signal loss due to recombination in the depletion region is also reduced. This mode is the preferred one for a photodiode.
2.2 MOS and MOSFET

The devices called MOS (Metal-Oxide-Semiconductor) and MOSFET (Metal-Oxide-Semiconductor-Field-Effect-Transistor) are based on p-n junction. The traditional MOS structure is obtained by a layer of silicon dioxide ($\text{SiO}_2$) between a layer of metal and a doped silicon substrate. Since the silicon dioxide is a dielectric material, its structure is equivalent to a planar capacitor, with one of the electrodes replaced by a semiconductor.

![Figure 2.4: Metal-oxide-semiconductor structure on p-type silicon: no charge (a), charged (b), [3].](image)

When a voltage is applied across a MOS structure, it modifies the distribution of charges in the semiconductor. If we consider a p-type semiconductor, when a positive voltage is applied, the positive charges go away from the creating depletion layer. If the voltage is high enough, a concentration of negative charge carriers is created near the interface between the semiconductor and the insulator, fig. 2.4.

![Figure 2.5: N-channel MOSFET (enhancement type): (a) 0 V gate voltage, (b) positive gate bias, [3].](image)

A metal-oxide-semiconductor field-effect transistor is based on the mod-
ulation of charge concentration by a MOS capacitance between an electrode and a gate located above and insulated from all other device regions by a dielectric layer which is an oxide, such as silicon dioxide. Compared to the MOS capacitor, the MOSFET includes two additional terminals, source and drain, each connected to individual highly doped regions that are separated the body region. These regions can be either p or n type, but they must both be of the same type, and of opposite type to the body region, which is less doped.

There are two types of MOSFET: the enhancement MOSFET and the depletion MOSFET. We describe the enhancement type. It is possible to analyze the other type by changing the polarities of the region and the voltages. Figure 2.5 shows a schematic picture of the n-type MOSFET or nMOSFET (enhancement MOSFET). In absence of bias voltage applied to the gate terminal, there exist two consecutive pn junctions between the drain and source and no current flows from drain to source. When we apply a voltage $V_{GS}$ between the drain and source, because of the oxide layer under the gate electrode, the gate current will be essentially zero, but two things happen:

- free holes in the p-type substrate are repelled from the region under the gate leaving "uncovers" bound negative charges;
- Electron from the heavily doped N+ regions are attracted under the gate.

These effects create an induced n-type channel: only when the $V_{GS} \neq 0$ the channel is formed, on the other hand under the gate there are not charges. If a voltage $V_{DS}$ is applied between the drain and the source, we will have a flow of electrons from source to drain. The nude acceptors, as we can see in the MOS case, built the inversion channel. Adjusting $V_{GS}$, it is possible to control the electron density in the channel, and then the current.

Unlike the MOS, where the inversion layer electrons are produced slower, through carrier generation and recombination centers in the depletion region, in the MOSFET capacitor they are supplied very quickly from the source/drain electrodes.

### 2.3 CMOS circuit and imaging application

The Active Pixel Sensor, or APS, is a matrix composed by a large number of pixels, in which, for each of them, there are a simplest form of CMOS circuits, composed by a photodiode, an amplifier and different MOSFETs.

The typical scheme of a pixel is illustrated in the fig. 2.6. The circuit is composed by a capacitor $C$, a p-MOS transistor, $M_1$ and by two n-MOS
transistor, $M_2$ and $M_3$. The digital signal Reset and RowSel, row selection, control the gates of $M_1$ and $M_3$, while $V_{DD}$ is the pixel supply voltage, [6].

The photodiode, when it is hit by light, allows the passage of the current between anode and cathode proportional to the light intensity. The photodiode is in parallel with the capacitor, which is the sum of the diode junction capacity and the input capacity of $M_2$ gate.

Before the exposure to the light, the Reset control, which sends in conduction the $M_1$ MOS, leads the capacitor at voltage $V_{DD}$, biasing inversely the photodiode. During the integration time, $t_{int}$, the photodiode, connected to a capacitor in parallel, permits to the current $I_{ph}$ to pass and then to discharge with the time the capacitor $C$, lowering the gate voltage of $M_2$ until to the value $V_{lux}$:

$$V_{lux} = V_{DD} - \frac{I_{ph}t}{C}. \quad (2.3)$$

The potential $V_{lux}$ is transmitted to the $M_2$ source, which is an amplifier (source follower). When RowSel is high, $M_3$, the signal passes to the analog to digital converter and it will be sent to the common line of the pixels of the same column. When the readout is ended $M_3$ returns low, $M_1$ becomes high, so that p-MOS is turned-off, and the new cycle begins [6].

A pixel array (fig. 2.7) is accessed one row at a time by enabling all the row-select transistors within the single row of pixels. At the bottom of the array, the individual pixels within the row are selected and read out column by column,[19].

Figure 2.6: 3-Transistor CMOS Active Pixel sensor, [6].
For imaging applications, the signal from the photodiode is integrated and its accumulation provides a form of statistical binning that is a more faithful representation of light intensity that falls on the pixel.

The accuracy in image acquisition, high resolution, and very low noise of these devices are characteristics more promising. For this reason was choose a CMOS photosensor, that will be presented in the next chapter together with the triple-GEM device that was used for the measurements described in chapters 4 and 5.
Chapter 3

The GEMs optical readout

In this chapter the principal of operations of the optical readout of a triple GEM detector are described. The device structure, together with the main optical parameter, and the sensor are presented.

3.1 The origin

The aim of the experiment performed by Fraga et al [8] was the detection of thermal neutrons by a triple-GEM device filled with $^3\text{HeCF}_4$. The triple-GEM system had an optical readout obtained with a CCD camera equipped with a standard 50 mm f:1.8 photographic lens and cooled to -30°C.

Figure 3.1 shows the images of proton and tritium tracks recorded by Fraga et al [8] by means of a CCD looking at a triple GEM structure. The structure of the tracks is clearly seen in most events.

Figure 3.2 shows two images of tracks and the respective distributions of the scintillation light along the longitudinal CCD pixels of the track projection. The light variation along the tracks, due to the different energy deposition curves of the proton and the tritium, were identified [8].

The results obtained by this study are an example on how it is possible to extract informations about the tracks of charged particles from the study of acquired images. The choice to perform a tracker based on a triple-GEM structure filled with a mixture that comprises $CF_4$ gas, derives by this and other studies. For optical readout, however, the use of a CMOS sensor has been chosen.
Figure 3.1: Images of proton and triton tracks obtained with HeC$\text{F}_4$ mixture, [8].

Figure 3.2: Distribution of measured scintillation along tracks. The Bragg curves of the proton (left) and tritium (right) are revealed. [8].
3.2 The ORANGE prototypes

The name ORANGE is the acronym for a particle tracker based on optically readout GEM. The light production associated to the electron multiplication, due to the passage of a charged particle through $He/CF_4$ gas mixture in the triple-GEM detector, allows to perform an optical read out. The big progress achieved in CMOS-based photosensors, even in commercial CMOS cameras, allows to obtain images with a very visible signals from minimum ionizing particles.

3.2.1 Triple-GEM based detectors

In this section we will present the layout of two prototypes: the first associated to the lab measurements [13], while the second used during tests on beam.

The two detectors are composed by triple GEM structure, which was obtained by stacking three $10\times10\,cm^2$ standard GEM foils. These foils are perforated with holes that have a bi-conical shape, whose diameter varies between $70\,\mu m$ and $150\,\mu m$, as mentioned in chapter [1]

![Figure 3.3: Drawing (not to scale) of the triple GEM stack of the second prototype.](image)

In fig. 3.3 it is possible to see a section of the second prototype system. The drift gap is the sensitive region of the device that occupies the larger volume than the other gaps; the ionization process takes place here where the primary electrons are produced. The two triple-GEM structures differ for the sizes of this gap: in the first prototype, the drift volume is high $3\,mm$ while in the second is $10\,mm$, then, the collection volume covers respectively
The first transfer gap is between the first and the second GEM, while the second transfer gap is between the second and the third GEM; both gaps have a thickness of 2 mm. In these regions the clouds of electrons are carried through the three GEM foils.

Seven different high voltage channels are used to supply the detector electrodes through $1 \, \text{M} \Omega$ protection resistors. The electrons created in the multiplication process induce a signal on the copper surface of the last GEM.

To allow the external readout of the light, the two prototypes have a transparent window: for the first detector, this is formed by a transparent foil while, in the second, it is replaced by a plexiglass tile, 6 mm thick. Both of them are placed in front of the last GEM closing the gas volume.

In fig. 3.4 it is possible to see a picture of the second triple GEM stack assembled in clean room; the drift gap is clearly visible. Both the triple-GEM structures are placed in a black box, equipped with an upper window used for the image acquisition, which is placed right above the transparent cover.

### 3.2.2 Gas mixture

The gas mixture used in this device is composed by $HeCF_4$, whose percentages were chosen from the results obtained from previous studies \cite{13}. The carbon tetra-fluoride $CF_4$ has important properties: it provides high electron drift velocities, low electron diffusion and it is a good and fast scintillator.

The optical emission spectrum of the $CF_4$ shows two peaks: the first in a range between 200 -350 nm and the second between 500-800 nm, see fig. 3.5.

The peaks in the visible region result from the excitation of a Rydberg
Figure 3.5: Light intensity, normalised to the current, as a function of the wavelength for $HeCF_4$ (60/40). [9].

state of $CF_4$ molecule that dissociates emitting $CF_3$ fragment; the threshold energy for this emission is 12.0 eV. The UV band seems to originate by $CF_4^+$ ion that forms unstable molecular states and ionization processes, which are generally dissociative. One of the dissociation channels leads to the formation of an emitting $CF_3^+$ ion that could be responsible for the UV emission, [9].

3.2.3 The optical system

To understand and optimize the light emitted by the gas, it is necessary to study the main equations which characterize the optical system, [11].

The device is composed by a CMOS camera equipped with a suitable lens. By using the thin lens approximation and simplifying the lens as a single converging lens, we can describe what happens when the light passes through the optical system.

A lens is a transmissive optical device that focuses or disperses a light beam through the refraction. The axis that pass through the physical center of the lens is the optical axis. With reference to fig. 3.6 we can see the lens indicated by $L$ and its center, indicated by $O$. The object that emits the light is $y$ that is at a distance $s$ from the point $O$; the image of the object ($y'$) is placed at a distance $s'$ from the point $O$. The primary focus $F$ is a point of the lens axis in which each ray, that comes from it or that is directed towards it, is propagated parallel to the axis due to the refraction. The secondary focus $F'$ is a point of the lens axis in which each ray, that is
Figure 3.6: Schematical pictures on how an image is created by converging lens.

propagated parallel to the axis, is directed in it or appears to come from it, due to refraction. The distances of $F$ and $F'$ from lens are individuated by $f$ and $f'$, which are focal distances. In our case, the medium in which the light has been produced is the same in which the image is created, then, the refractive index does not change and this implies that $f = f'$.

Because of the proportionality between the triangles $\triangle QST$ and $\triangle FOT$, and between $\triangle QST$ and $\triangle FOS$ it follows (fig. 3.6):

$$\frac{y - y'}{s'} = \frac{y}{f'} \quad y - y' = -\frac{y'}{f}$$

which leads, with $f = f'$, to the conjugated points formula:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

Furthermore, by looking at triangles $\triangle MOQ$ and $\triangle M'OQ$:

$$\frac{s}{y} = \frac{s'}{y'} \quad \frac{y'}{y} = \frac{s'}{s}$$

and also for triangles $\triangle MFQ$ and $\triangle FOS$, we can write the magnification $I$ as:

$$I = \frac{s'}{s} = \frac{y'}{y} = \frac{f}{s - f}$$

The following cases are possible:
• $s < f \rightarrow$ virtual image;

• $f < s < 2f \rightarrow y' > y$ and $s' > s$: larger image;

• $s = 2f \rightarrow y' = y$ and $s' = s$: equal and equidistant image;

• $s > 2f \rightarrow y' < y$ and $s' < s$: reduced image.

The magnification can be either described with another formula considering the other side of the lens, i.e. looking at the triangles $\triangle TOF'$ and $\triangle FMQ'$:

$$I = \frac{s'}{s} = \frac{y'}{y} = \frac{s' - f}{f} \quad (3.5)$$

Another important element to take into account is the diaphragm of the lens: the amount of light that arrives to the sensor depends strongly on it. In the case of isotropic light emission, the photons reaching the sensor depend both on the distance and on the diaphragm of the lens. The lens aperture is defined as $\# = f/d$, where $f$ is the focal length and $d$ is the diaphragm diameter.

If the source is at a distance $s$, enough far from the lens so as to be considered point-like, the fraction of the photons that pass through the lens can be derived by

$$\Omega = \frac{\pi \left(\frac{d}{2}\right)^2}{4\pi (s)^2}, \quad (3.6)$$

which represents the geometrical acceptance.

Starting from the second magnification equation 3.5 we can find:

$$s' = (I + 1)f \quad (3.7)$$

and inserting it into the above equation:

$$\Omega = \frac{\pi \left(\frac{d}{2}\right)^2}{4\pi (s')^2} = \left(\frac{d}{4(I + 1)f}\right)^2 \quad (3.8)$$

whence, remembering how the aperture of the diaphragm is defined we have:

$$\Omega = \frac{1}{(4(I + 1)\#)^2}. \quad (3.9)$$

which represents the fraction of the photons that reach the camera sensor.
3.2.4 The camera

In this work we use a ORCA-Flash 4.0 camera based on a CMOS image sensor and instrumented with a Schneider lens. The progresses that have been achieved in recent years for this type of sensors have led to the choice of this camera: speed in the acquisition and image sharpness, low noise, high sensitivity, are its characteristics. In fig. 3.7 we can see a picture of the camera equipped with its lens.

![Camera Picture](image)

Figure 3.7: Picture of the camera.

The CMOS sensor is composed by $2048 \times 2048$ pixels with an area of $6.5 \, \mu m \times 6.5 \, \mu m$ for a total sensitive surface of $13.3 \, mm \times 13.3 \, mm$ providing, then, a high granularity (4 Mega Pixels).

The structure of the pixels consist of circuit that converts the incident light in electric signal by a photodiode and then into voltage within the pixel\textsuperscript{1}. There is an on-chip column amplifier to achieve higher speed, allowing the simultaneous parallel readout of the signal. This allows low-noise and high-speed signal readout.

The element of CMOS image sensor is divided into upper and lower, each of which is placed with an on-chip column amplifier. This allows the simultaneous readout of two horizontal lines, achieving higher speed, fig. 3.8. The image readout starts from 2 central lines, the upper one of which moves toward the upper end and the lower one toward the lower end.

An important factor in determining the sensitivity is the efficiency in converting the light in to electric charge, or quantum efficiency. Since CMOS image sensor has multiple amplifiers arrayed in one pixel, the sensor unit that

\textsuperscript{1}See Ref. \textsuperscript{[2]}. 
performs the light-to-charge conversion is limited to a part of the pixel. Each pixel is equipped with an on-chip microlens, achieving increased sensitivity
in comparison with the conventional CMOS image sensor. The sensibility of this device is about 70% for the visible wavelength range and, specifically, it reads the signal right that is around 600 nm (see fig. [3.9]).

3.2.5 The Schneider lens

We used a Schneider Fast C-Mount Lens, adapted to reproduce the image of the track on the sensor of the camera. The lens has a focal length equal to 25 mm and a maximum aperture of f/0.95. This was required to collect the largest possible number of photons that come from sensitive area.

The optical system, then, was also equipped with a 1 mm ring spacer between the lens and the sensor which allowed to obtain the effective focal lens to about 20 mm. At a distance of about 20 cm:

- each pixel looks an area of 50 $\mu$m $\times$ 50 $\mu$m.

- the image of $10 \times 10$ cm$^2$ of the GEM can be acquired at a distance of 20 cm.
Chapter 4

Laboratory measurements

This chapter summarizes the results achieved in different tests performed in laboratory. The measurements presented, are of different types:

- acquisition of the light by a phototube;
- study of the camera performance;
- optimization of the camera focus;
- tracking of the cosmic ray muons.

The obtained results were used as a starting point for the measurements on beam presented in the chapter 5.

4.1 Measurements with phototube

4.1.1 Experimental setup

The detector was placed with the GEM foils in horizontal position. For this measurements we used a prototype with the drift gap size about 3 mm. When the cosmic rays pass, two NaI scintillators, placed one above the GEM structure and one below, permits, through the signal coincidence, the acquisition of the events. The sensitive areas of the scintillators are about 100 $cm^2$.

The light produced by the avalanche in the channels of the third GEM was collected by a R9800 photo-multiplier with a window diameter of 25 mm (GEM-PMT). The signal produced by both the NaI PMT and by the GEM-PMT were acquired by the oscilloscope Lecroy WavePro 7300 10 GS/s.
CHAPTER 4. LABORATORY MEASUREMENTS

4.1.2 Optimization of electric field

The measurements of the light yield, [12], were performed by using a binary gas mixture Ar/CF$_4$ (95/5). A Garfield simulation was done to evaluate the main characteristics of the gas mixture.

As shown in fig. 4.1 the drift velocity has its maximum for low fields and thus decreases and saturates. It was calculated that a minimum ionizing particle has the capability of creating about 12 clusters in the 3 mm wide drift gap that means an average one cluster every 250 $\mu$m. About 2.5 electrons per cluster in average are expected for a total of about 28 primary electrons, [12].

![Figure 4.1: Drift velocity as a function of the electric field, [12]](image)

Event by event the charge collected was integrated and in fig. 4.2 an example is shown. The distribution of the integrated charge has a landau trend with a peak equivalent to 1 pC.

With this arrangement, it was possible to perform a study of the light yield as a function of electric fields, that are shown in the fig. 4.3. The amount of light, collected at the bottom, is almost stable for values of drift field comprised between 0.5 kV/cm and 1.5 kV/cm. On the other hand, for transfer fields it is possible to see a maximum around 1.5 kV/cm.

The photomultiplier response to a single photo-electron was measured by using a calibrated source. In the optimized field configuration about 170 photo-electrons were collected in average for a minimum ionizing particle crossing. The arrival time of the signals was evaluated by comparing the
CHAPTER 4. LABORATORY MEASUREMENTS

Figure 4.2: Examples of charge spectrum obtained by integrating the GEM-PMT waveforms. The GEM stack was filled with Ar/CF$_4$ (95/5).

Figure 4.3: Light yield as a function of electric fields as obtained with Ar/CF$_4$ (95/5) gas mixture. [12].
measurements obtained with those extracted by simulation as a function of electric drift field applied on 3 mm gap.

Figure 4.4 shows that this time as a function of the drift field follows the behaviour of simulated drift velocity. Unfortunately, this amount of light results to be too small to allow the reconstruction of the tracks with the camera.

Figure 4.4: Signal arrival time as a function of the electric field applied in 3 mm drift gap.

For this reason the ArCF₄ gas mixture was replaced with HeCF₄ (60/40) and the situation significantly improved. An example of the waveform of acquired signal is shown in fig. 4.5. These signals were analyzed to evaluate the charge collected by the GEM-PMT.

Figure 4.6 shows the integral of the charge collected with a superimposed "Gauss+Landau" fit. From the results of fit it was possible to extract the pedestal value and the most probable value of the charge: it was 100 times larger than the corresponding value obtained with ArCF₄ mixture.

By the study of the behaviour of the total charge integrated with the GEM-PMT it was possible to optimize the electric fields between the GEM, and then the light yield. The following measurements were carried out by setting the transfer fields to a certain value and by varying the field of drift and, subsequently, the opposite.

As it is possible to see from fig. 4.7 and fig. 4.8 the amount of collected light has a maximum for drift values around 1.5 kV/cm while the amount of light increases for fields in the transfer gaps from 1.0 kV/cm until 2 kV/cm and then it becomes almost stable.
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Figure 4.5: Example of several superimposed waveforms acquired by the GEM-PMT, [13].

Figure 4.6: Examples of a charge spectrum obtained by integrating the PMT waveform with a superimposed "Gauss+Landau" fit, [13].
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Figure 4.7: Light yield as a function of the drift electric fields obtained with the gas mixture $HeCF_4$ (60/40), [13].

Figure 4.8: Light yield as a function of the transfer electric fields obtained with the gas mixture $HeCF_4$ (60/40), [13].

4.2 Performance of the CMOS based camera

After the optimization of the electric fields of the triple-GEM system, the CMOS sensor performance was verified.
Figure 4.9: Response of the camera as a function of number of photons in the spot, [13].

By means of 1 mm diameter calibrated light source, the linearity of the response was tested. The fig. 4.9 shows the behaviour of the camera response as a function of the number of sent photons in 1 mm diameter spot. From the superimposed linear fit is shown that at 0.91 counts per photon were found,
The camera was then put in the dark and the response of a single pixel was studied in order to evaluate the noise behavior. The nominal noise for each pixel is about 2 photons, [2].

In fig. 4.10 the response distribution of a single pixel, obtained by acquiring 600 events, is shown with a Gaussian fit. As expected, the sigma is below than 2 counts, i.e. 2 photons.

4.2.1 Hot spots

A particularity of the GEM structure was noted when the used gas mixture was composed by ArCF₄. Thanks to the possibility of detecting very few photons, a small continuous hot spots in the triple GEM detector were found, as we can see in fig. 4.11.

![Figure 4.11: On the left, a picture of the hotspots in the GEM system. On the right there is a zoom of one hotspot; the fine structure of the GEM holes is also visible, [12].](image)

Even if the leakage current was the order of few nanoamperes these spots appear when the high voltage reaches the operating values and their intensity increases with the gain. These white points are used to find the focus position.

The better focus position was obtained by analyzing images achieved at different distance ($d$) between sensor and the sensitive area with $d$ that varies from 18 cm to 21.5 cm by $\approx 2.5$ mm steps, see fig. 4.12.

In fig. 4.13 we can see an example of the hot spot chosen to find the focus position: the image above shows that the sensor was not in focus position.
Figure 4.12: Schematic picture of focus calibration.
Figure 4.13: Images obtained by the optical system. We can see, on the top, examples of the micro-discharges that are not in focus, compared to those that are at focus position.

The dimension of the hot spots in pixels were acquired as a function of the camera distance. For each picture it was possible to find the number of pixels to evaluate the point sizes, see fig. 4.14. The position that minimizes the sizes (i.e. $d \simeq 20\text{ cm}$) was chosen as the optimal one.
Figure 4.14: Focus position in a sensor plane along the x-y axes.
Since we are working with $I \sim 10$ from formula 3.5 and with a diaphragm diameter of 26 mm we can evaluate an effective focal length with the spacer of 18 mm and thus an $#_{\text{eff}}$ of about 0.69. The geometrical efficiency of photosensor can be evaluated by introducing this values in the formula 3.9 and it results $\epsilon_g = 1.1 \cdot 10^{-3}$. The same efficiency can be evaluated from the geometrical parameters:

$$\epsilon_g = \frac{\pi \left(\frac{d}{2}\right)^2}{4\pi (s)^2} = 1.2 \cdot 10^{-3}.$$  \hspace{1cm} (4.1)

As it is possible to see the results obtained are compatibles.

### 4.3 Cosmic ray and electron measurements

To observe long tracks released by cosmic rays, the detector was put in vertical position, so that the muons pass through the drift zone almost parallel to the GEM plane. In the pictures 4.15, we can see two examples of tracks acquired with an exposure time of 100 ms.

![Figure 4.15](image)

Figure 4.15: Examples of cosmic track images acquired by CMOS based camera, [13].

The amount of light produced by this types of tracks was evaluated analyzing the image on the right in fig. 4.15. The light distribution detected by the pixels in the track region and by pixels not illuminated by the track is shown in fig. 4.16.
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Figure 4.16: Distributions of the pixel response inside and outside the region illuminated by the track, [13].

Figure 4.17: Maps of the pixels with a response larger of thee sigmas respect to the pedestals, [13].

The superimposed Gaussian fit provides the average value of the response of not illuminated pixels around 99±2 counts, in good agreement with the
results obtained in the dark condition. Up to 30 photons are detected by
each illuminated pixel.

The total amount of light integrated by the pixels in the track region was
evaluated by studying the recorded images. It was measured that the linear
light collection density is of about 600±60 photons per track millimeter.
From Garfield simulation, [13], the electrons produced per millimeter by a
cosmic ray was evaluated to be around 7.7 and therefore 80 photons are
detected per primary electron.

The maps of the pixels with a response of about three sigmas larger than
the pedestals, or else higher than 105 counts, are shown in fig. 4.17. From the
analysis of all recorded muon tracks, an amount of 40±5 pixels, satisfying
the above requirement per track millimeter, was measured.

4.3.1 Electrons measurements

Very bright and short tracks were acquired during the muons data taking,
likely due to electrons coming from the natural radioactivity, fig. 4.18.

![Figure 4.18: Examples of electrons tracks, [13].](image)

The tracks are approximately, 2.7 cm (left) and 1.6 cm (right) long. As it
is visible from their intensities, the ionization density of these track is quite
larger than ones produced by cosmic ray muons.

Also in this case the maps of pixels, that exceeded the same threshold
used for the tracks of the muons, were obtained (fig. 4.19). About 300 pixels
three sigmas above the pedestal per track millimeter were measured.
4.3.2 Study on the gas mixture

By using the muon tracks, it was possible to study the performance of the gas mixture, allowing to choose between two different ratios of the same gases.

In a range between 420 V to 480 V we can see the behavior of light yield as a function of the GEM voltages for two gas mixture: $HeCF_4$ (40/60) and $HeCF_4$ (60/40), fig. 4.20.
Setting the electrics field to a value $E_d = 1 \text{ kV/cm}$, $E_t = 2 \text{ kV/cm}$, we can see that while a 60% of $CF_4$ allows to reach higher voltages, the mixture with 40% $CF_4$ shows a total light collection more than two times larger in the whole studied range \[13\]. The choice, finally, falls on the gas $HeCF_4$ (60/40) mixture.
Chapter 5

Measurements at Beam Test Facility

This chapter presents the results of various tests on beams achieved at the Beam Test Facility (BTF) of the Frascati National Laboratories [1]. The responses of the detector were analyzed through simple algorithms and compared with results obtained by a simulation program.

5.1 The Beam Test Facility

The DAFNE Beam-Test Facility (BTF) is a beam transfer line designed for the optimized, stochastical production of single electrons/positrons for detector calibration purposes, or the extraction of the DAFNE LINAC electron/positron beam, [15].

The main system consists of a LINAC capable of producing packages of electrons and positrons with a frequency of 50 Hz within an energy range between 300-700 MeV for the $e^-$ and 300-550 MeV for the $e^+$. The aim of the LINAC is to inject the beams produced in the accumulation ring of $\text{DAΦNE}$, by setting the beam energy to 510 MeV for the meson $\Phi$ creation.

Along the beam trajectory there is a pulsing magnet that bends the particles in to the BTF area, equipped by different devices for the users. Among these, there is MEDIPIX 1 system that allows to study the multiplicity and the size of the bunches. In table 5.1 the values of the beam parameters that can be set by the users are shown.

The beam energies that we have used are in the range between 50 MeV e 450 MeV, the average multiplicity equal to 1 and the transverse dimension of about 1 mm.

The triple-GEM structure was placed in the experimental hall with the
Figure 5.1: Picture of ORGANGE at the Beam Test Facility of the Frascati National Laboratories.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average maximum flow</td>
<td>(3.125 \times 10^{10}) particles/s</td>
</tr>
<tr>
<td>Transverse beam size (x)</td>
<td>1 - 25 mm</td>
</tr>
<tr>
<td>Transverse beam size (y)</td>
<td>1 - 55 mm</td>
</tr>
<tr>
<td>Divergence</td>
<td>1 - 2 mrad</td>
</tr>
<tr>
<td>Energy</td>
<td>25 - 500 MeV</td>
</tr>
<tr>
<td>Multiplicity (particles/bunch)</td>
<td>1 - (10^5)</td>
</tr>
</tbody>
</table>

Table 5.1: Settable parameters by the users to the BTF \[1\].
GEM foils in vertical position and with the drift gap centered with respect to the exit point of the beam (fig. 5.1).

5.2 Gain

The first performed analysis concerned the gain of the GEM: its absolute value and its behaviour as a function of the GEM voltage.

5.2.1 Acquisition of the waveforms

The first measurements carried out at the BTF were made by acquiring the individual pulses of the induced signals on the bottom electrode of the last GEM by the secondary electrons. By a simulation program called Garfield, the properties of the gas mixture were evaluated. The program, among many functions, takes into account the processes that occur during the ionization of a particular mixture of gases by a charged particle. The results are shown in fig. 5.2: 400 MeV electrons were simulated with a path of 10 cm in the drift gap. At this energy we expect that the incident electrons produce \( \approx 340 \) clusters, which are composed of about 2 electrons.

The drift velocity as a function of the values of electric fields was simulated. As we can see in fig. 5.3, at an electric drift field of 1.5 kV/cm in a region thick 1 cm corresponds a drift time about 250 ns.

For these measurements, the energy of the beam was set to 400 MeV with multiplicity very low in order to have single electrons passing through the sensitive area of the detector. The acquisition system was triggered externally by two NaI scintillators. The electric fields of the triple-GEM were set up in two configurations:

**Set1:** \( E_d = 1.0 \text{ kV/cm} \) and \( E_t = 1.5 \text{ kV/cm} \)

**Set2:** \( E_d = 1.5 \text{ kV/cm} \) and \( E_t = 2.0 \text{ kV/cm} \).

The acquired events were collected having set the voltages of each GEM to the values of 430 V, 440 V, 445 V and 450 V. The signals were sent to an oscilloscope Lecroy WavePro 7300 10 GS/s through a 1 MΩ input impedance. The oscilloscope acquired 10 Msamples/s and had a 10 ms window. This window was divided in two parts with the trigger in the centre: in the first, 5 ms, the noise behaviour was evaluate, while in the second part the signal due to the charged particle was collected, (see fig. 5.4).

Since each event can contain one or more electrons, what we want is to isolate the signals due to the single electron, discarding the others. For each
CHAPTER 5. MEASUREMENTS AT BEAM TEST FACILITY

Figure 5.2: From Garfield simulation: the number of clusters produced when 400 MeV of electron passes through the gas and the number of electrons per cluster.

Once the single electron signals were isolated, we calculated the charge collected by the detector by integrating the waveforms. Since the signals doesn’t return to zero, we fit its shape as shown in fig. 5.6. For the fit function the product of a Fermi Dirac, for the rising part, and a negative
Figure 5.3: Average drift velocity of electrons as function of the electric field values.

Figure 5.4: Example of the signal induced on the bottom electrode of the last GEM as acquired through a 1 MΩ input impedance.
CHAPTER 5. MEASUREMENTS AT BEAM TEST FACILITY

Figure 5.5: Histogram of the maximum amplitude exponential, for the descent part, was used.

Figure 5.6: An example on how the fit function works.

Event by event the resulting fit was integrated to calculate the collected charge. Figure 5.7 shows an example of distribution of charge.

The results obtained from the Gaussian fit are reported in the tables (5.2) and (5.3) corresponding to the two different settings of the electric fields.

From the obtained charges we get the number of collected electrons. By dividing this number by the number of primary electrons produced by ion-
CHAPTER 5. MEASUREMENTS AT BEAM TEST FACILITY

Figure 5.7: Gaussian fit on the value of the charge for a data samples.

Figure 5.8: Gaussian fit on the value of the charge for a data samples.

Table 5.2: Integral of the waveforms for $E_d = 1.0$ kV/cm and $E_t = 1.5$ kV/cm. The voltage refers to that applied between each GEM.

<table>
<thead>
<tr>
<th>SET 1</th>
<th>Voltage (V)</th>
<th>Charge (pC)</th>
<th>Error (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>122</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS</td>
<td>16.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>8.098</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>124.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sigma</td>
<td>17.96</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For all experiments reported below, the electric fields were set to the values given by the Set 1.
Table 5.3: Integral of the waveforms for $E_d = 1.5$ kV/cm and $E_t = 2.0$ kV/cm. The voltage refers to that applied between each GEM.

Figure 5.8: The gains for the two different electric fields settings. The circles correspond to the setting with $E_d= 1.0$ kV/cm and $E_t = 1.5$ kV/cm (set 1); at the squares correspond $E_d= 1.5$ kV/cm and $E_t = 2.0$ kV/cm (set 2).
5.3 Tracking

The tracking of charged particles by acquiring images of photons emitted by the gas mixture is the purpose of this device. The acquisition of the camera can be set choosing the most suitable exposure time for each measurement, although asynchronously and without the external trigger. A simple tracking method was developed to identify and study the tracks of electrons of the beam in the detector.

5.3.1 Algorithm

The camera images are written on files that consist of a set of $2048 \times 2048$ values, corresponding to the response of each individual pixel. These images are reconstructed, by a simple C++ program, as two-dimensional histograms, fig. 5.9.

![Figure 5.9: Picture of an event that contains many tracks.](image)

Between all acquired images the ones containing a single track are selected. Each image is subdivided in 200 vertical slices and the maximum of each slice is found. If it is above a certain threshold a Gaussian fit is performed around it.

The mean values of each Gaussian function are thus taken as cluster position and used to perform a linear fit to the 2D projection of the trajectory of the charged particle as shown fig. 5.10.

Once the track position is located, the collected light is integrated in a rectangle around it. To find its optimal width we analyzed the integrated
CHAPTER 5. MEASUREMENTS AT BEAM TEST FACILITY

Figure 5.10: Example of a reconstructed electron track.

Figure 5.11: Integrated photons per different rectangle dimensions. In the x-axis there are the sizes of the transverse side of the rectangle counted from the fitted track.

charge by using rectangles of different dimension.

The fig. 5.11 represents the behaviour of the integrated light as a function of the transverse side of rectangle. Our choice is to set this size to 9 pixels, in order to maximize the signal while containing the noise.
5.3.2 Results

By using the above described algorithm, we reconstructed the tracks and studied their characteristics.

As we have seen in fig. 5.10, the linear fit follows the maximum of cluster position along the particle track. Fig. 5.12 represents the longitudinal profile of the collected light [14]. The cluster structure is well visible.

Figure 5.12: Longitudinal profile of the light collected in the track of fig. 5.10 [13].

Figure 5.13 shows the transverse profile of the track. The obtained illumination has a Gaussian shape with a sigma of about 5 pixels (or 250 $\mu m$).

Figure 5.13: Average transverse profile of the light collected of the track of fig. 5.10 [13].
5.3.3 Space resolution

Figure 5.14 shows the distribution of the residuals of the reconstructed clusters to the linear fit and provides an evaluation of the space resolution and tracking capability of the device. The results were obtained with a set of 20 single tracks of 480 MeV electrons. A space resolution of the triple-GEM detector of about 70 $\mu m$ was evaluated.

Figure 5.14: Distribution of the residuals of the reconstructed clusters to the fitted track, [14].
5.4 Light yield measurements

To maximize the light yield, we have studied its behaviour as a function of different parameters:

- GEM voltage, in section 5.4.1
- particle energy, in section 5.4.2

In the following sections these measures and their results will be exhibited.

5.4.1 Dependence on the GEM voltage

The study about how the light yield varies with the GEM voltages was done by setting the beam energy at 450 MeV and with an exposure time of camera of 0.1 s. The voltage across the three GEM foils is changed into a range between 430 V and 480 V, with steps of 10 V.

To the number of photons into the chosen rectangle around each track, the integral of the counts in a not illuminated rectangle, with the same size, is subtracted. An example of the distribution of the results obtained for a run with superimposed a Gaussian fit is shown in fig. 5.15.

Figure 5.15: Example of the distribution of the integral of the number of the photons collected in the chose rectangle, once that the integral value of the noise rectangle was subtracted.
Figure 5.16: Light yield as a function of the sum of voltages of the GEM.

Figure 5.17: Behaviors of the number of electrons and photons as a function of the sum of the GEM voltages.
Figure 5.18: The ratio between the number of photons and of electrons as a function of the triple-GEM gain.

Figure 5.16 shows the behaviour of the emitted light as a function of the sum of the GEM voltages, as obtained from the Gaussian fit. It is possible to see that the number of photons increases exponentially with the voltage. It can be useful to compare the light yield as a function of the GEM voltage with the number of collected electrons at the same voltage, see fig. 5.17.

The trend of the two sets of data, although correspond to a different magnitude, is quite similar and this consideration can be verified from the analysis of the ratio between the number of photons and electrons, shown in fig. 5.18 as a function of the gain (obtained in the section 5.2.1). The ratio is almost constant around 0.07 and confirms what has been achieved by another group [10].

5.4.2 Dependence on the particle energy

Another important parameter to be studied is sensitivity of the device to the density of energy released in the gas. This parameter can be very useful for measuring the total energy of the crossing particle or to individuate its identity. In order to perform this study, we exploited the possibility of changing the beam energy.

The voltage between each GEM for these measurements is set at 470 V and the exposure time of the camera at 0.1 s. The energy scan was done in a range between 50 MeV and 400 MeV with steps of 50 MeV.
CHAPTER 5. MEASUREMENTS AT BEAM TEST FACILITY

By means of Garfield, the average number of clusters produced by an electron in 10 cm of $HeCF_4$ (60/40) was evaluated for different beam energies. In the range from 30 MeV to 450 MeV, as shown in fig. 5.19, an increase in amount of clusters of about 6% is expected, while the average number of electrons per cluster is almost stable, fig. 5.20.

The increase in the density of the primary charge is expected to result in an increase of the collected light density. In order to analyze the experimental
data, images were subdivided in columns 16 pixel width. The amount of light in each column was evaluated.

The tracks are generally shorter than 10 cm and they appear in the central area of the image; to be sure not to contain any empty count, we have decided to integrate only the central part of the images, discarding the first and the last 512 pixels.

An example of the distribution of the amount of light per column with a superimposed landau fit is shown in fig. 5.21.

![Figure 5.21: Example of integral obtained from the slices with bases of 16 pixels.](image)

From this plot an amount of about 500 photons per slice is found that means about 600 photons per millimeter. Since from the simulation we know that about 7 primary electrons per millimeter are produced, we can conclude that, in this gain configuration, almost 100 photon per primary electron are collected.

The same analysis was performed for all the acquired beam energies and the results are shown in fig. 5.22. As expected, the number of photon collected per slice (i.e. the light collection density) increases with the beam energy.

By using the Bhete-Block formula for \( HeCF_4 \) (60/40) mixture, the energy release in 0.8 mm gas slice can be evaluated for the different beam energies.

Figure 5.23 shows that the number of photons collected per slice is strongly correlated with the amount of the energy release per slice. From the superimposed linear fit it can be evaluated that about 6 photons are collected per eV released.
Figure 5.22: Light collected in 0.8 mm slices as a function of the beam energy.

Figure 5.23: Light collected in 0.8 mm slices as a function of the energy released per slice according to the Bethe-Block formula.
Figures 5.24 shows the relative fluctuation of the light collection density, that decreases with the energy release per 0.8 mm. For energies larger than 200 MeV, a resolution of about 50% can be obtained.

Figure 5.24: Relative fluctuation of the light collected as a function of the energy released in 0.8 mm slices.

### 5.5 Tracking performance as a function of particle position

In order to study possible effects of particle diffusion in the drift gap, several measurements were taken by changing the detector position with respect to the beam, with 1 mm steps. The beam energy was set to 450 MeV with a very low multiplicity and the exposure time of the camera to 0.02 s.

Starting with an off beam detector position we collected 21 runs that correspond to a total displacement of 20 mm. Only 13 of those are interesting. The beam was expected to be at the center of the drift gap with the table in position of 268 mm.

For each track of each run we studied the transverse profile performing a Gaussian fit, as we can see in the fig. 5.25. The average values of the sigma of the Gaussian fit are shown as a function of the beam position in fig. 5.26.

The obtained results didn’t led to any evidence about the dependence of the detector performance as a function of the position. Very likely this is due to the beam divergence. Nominally this divergence should be very small.
Figure 5.25: Example of the transverse profile of a track.

Figure 5.26: Behaviour of the sigma values of the transverse profile as a function of detector position.
but, because of the distance between detector and beam exit point and of the presence of detector box materials in front, the beam spread in the device results large.

Figure 5.27: Number of the tracks collected per run during the position scanning.

Figure 5.28: Histogram of the intercepts of the tracks. The data studied refer to the condition in which the voltages between the GEMs were at 460 V and the beam energy was at 450 MeV.

In fig. 5.27 we can see the number of tracks collected in each position. If the effect of beam spread was negligible, we could have expected the graph
with a step trend. From the leading and the trailing edges of this plot, we can evaluate an effective beam spread of few millimeter (4-5 mm).

To check this results, we made some measurements on the distribution of the angles of the particles inside the sensitive volume. We used a high statistic run with a voltage of 460 V and we studied the distribution of the slopes and the intercepts of the tracks.

In fig. 5.28 is possible to see the distribution of the entry points in the gas volume. Figure 5.29 shows the fluctuation of slopes that is about 8.5 mrad. This spread is due in part to the initial beam divergence and in part to the multiple scattering due to the box walls.

![Histogram of the slopes of the tracks.](image)

Figure 5.29: Histogram of the slopes of the tracks. The data studied refer to the condition in which the voltages between the GEMs were at 460 V and the beam energy was at 450 MeV.

To evaluate the effect of the multiple scattering due to the materials present upstream of the sensitive volume, the initial beam divergence has to be subtracted. Figure 5.30 shows the trend of the slopes as a function of the corresponding intercepts and the superimposed linear fit.

By subtracting the slope obtained from the fit to that measured in the events, finally, the slopes due to the multiple scattering can be evaluated and result to be is about 7.9 mrad, see fig. 5.31.

The expected effect of the multiple scattering, can be evaluated by the formula [1.20]. The GEM structure is inserted in a black box thick 2.0 cm, formed by 1.5 cm of epoxy and 0.5 cm of PVC. The radiation length of the epoxy is 35 cm. Assuming the same value for the two materials, we can
Figure 5.30: The angular coefficient as a function of the intercept for each track collected in one data samples with a superimposed linear fit.

![Angular coefficient as a function of intercept](image1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/ndf</td>
<td>0.004781 / 85</td>
</tr>
<tr>
<td>$p_0$</td>
<td>$-0.113 \pm 0.01952$</td>
</tr>
<tr>
<td>$p_1$</td>
<td>$0.0001171 \pm 2.059e-05$</td>
</tr>
</tbody>
</table>

Figure 5.31: Histogram of the divergence due to the multiple scattering.

![Histogram of divergence due to multiple scattering](image2)

<table>
<thead>
<tr>
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</thead>
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</tr>
<tr>
<td>Mean</td>
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</tr>
<tr>
<td>RMS</td>
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<tr>
<td>Constant</td>
<td>17.7</td>
</tr>
<tr>
<td>Mean</td>
<td>$-0.0002392$</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.00793</td>
</tr>
</tbody>
</table>

Figure 5.31: Histogram of the divergence due to the multiple scattering.

estimate an angle spread due to the multiple scattering of about 7.2 mrad, in reasonable agreement with the measured value.

By subtracting in quadrature these values to the total angular divergence we can estimate a beam divergence of about 3.0 mrad, in good agreement with the nominal beam divergence of 2-3 mrad.
Conclusions

The optical readout of triple-GEM system has proved to provide very precious informations to reconstruct tracks of charged particles. Thanks of its high sensitivity and granularity, the use of CMOS sensor to collect the photons, allows to reach a very high level of accuracy.

In this thesis I describe the work and the measurements needed to assembly and optimize an optically readout Triple GEM device.

By means of two triple GEM prototypes, built in the clean room of the Physics Department of "La Sapienza" University, the first tests were carried out in laboratory to find to optimal working condition for the detector.

First of all, three different gas mixtures were tested with an increasing amount of CF$_4$. A 5% of CF$_4$ was already enough to provide light detectable by means of a PMT, but to small to allow for a proper exploiting of the CMOS sensor properties. Two mixtures He/CF$_4$ (60/40) and (40/60) were thus tested and showed to produce an amount of light large enough to be efficiently collected by the CMOS camera.

The electron transparency of the structure was analysed as a function of the electric field configuration. For all the mixtures a maximum of the efficiency in the charge transport was found for a field in the drift gap around 1 kV/cm and a field in the transfer gaps around 2 kV/cm.

In parallel, once the nominal CMOS sensor performance was tested and confirmed, the optical system was studied and optimised in order to be able to acquire the whole $10 \times 10 \, cm^2$ sensitive surface with the $1 \times 1 \, cm^2$ CMOS sensor maximizing the signal to noise ratio.

Having decided the main parameters of the device (gas mixture, geometry, electric configuration) its main characteristic were studied in details on electron beam at the Beam Test Facility of the Frascati National Laboratories.

The gas gain was studied. By using Garfield, the characteristics of the gas mixture were evaluated. The number of the primary electrons produced by a 10 cm track of 450 MeV electron was found to be about 340 clusters with about 2 electrons each. The results obtained from the simulation, together
with the measurements achieved with 10 GS/s scope, show that for a GEM voltage in the range 430-450 V, the gain is of the order of $5 \cdot 10^5$ until $1.3 \cdot 10^6$. The number of photons and electrons produced was evaluated for different GEM voltages reporting a constant ratio as a function of the gain of about 0.07 in the whole studied range.

Tracking algorithm was developed and allowed to analyze the images captured with the camera. About 1000 photons per track millimeters were measured for 450 MeV electrons. The transverse profile of each track has a Gaussian shape with a sigma of about 250 $\mu m$ and the distribution of the residuals respect to the expected direction for track have a sigma of about 70 $\mu m$. The last results provide an estimation of the spatial resolution of the tracker.

The light yield as a function of the beam energy was studied to test the sensitivity to different energy release densities. The amount of light collected in 0.8 mm gas slices of was studied for beam energies in a range between 50 MeV and 450 MeV. As the energy of the beam increases, the number of the collected photons increases while the relative fluctuations decrease until to arrive at a value of about 50% for high energy. The light collected in 0.8 mm slices as a function of the energy released per slice according to the Bethe-Block formula shows that about 6 photons are collected per eV released, section 5.4.2.

The tracking performance as a function of the crossing particle position allowed to evaluate the beam divergence that was found to be about 3 mrad, while the effect of the multiple scattering due to the detector box, expected to give rise to an angle spread of 8.5 mrad, was measured to be equal to 7.9 mrad.

The progress of technology connected with this type of system, has brought and will bring more and more important results. The results reported in this thesis work permit to find, to date, the better configuration for an innovative and versatile detector.
Bibliography


