Characterization and Calibration of a Triple-GEM Detector for Medical Applications

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Abstract

This project aimed to characterize and calibrate the triple Gas Electron Multiplier (triple-GEM) detector owned by the CRYOMAG research group at Universidad Nacional de Colombia, as well as to determine its possible applications in medical dosimetry. The detector’s response to various sources of radiation was characterized in terms of amplitude, duration, shape, and polarity of pulses, as well as its efficiency, gain, energy resolution, and temporal resolution. The triple-GEM detector’s energy proportionality was calibrated using the spectrum of an Iron-55 radioactive source. Then, the detector was used to measure radiation doses from this source using four different methods, as well as the dose from a medical portable X-ray machine at varying peak tube voltages and tube currents. Obtained doses were compared to reference values.

The characteristic properties of the detector were found to be an energy resolution of 19.5%, a temporal resolution of at least 40ns, and a maximum gain of $5 \times 10^6$. For the dose measurements, a calibration coefficient of $1.13 \times 10^4$ was obtained against the respective reference values of each source of radiation. There was a good agreement between the four dose-measuring methods for the Fe-55 source. It was concluded that the triple-GEM detector can be reliably used as a dosimeter, especially for nuclear medicine applications.

Keywords: Particle detectors, Detector characterization, Cosmic radiation, Radioactivity, X-rays, Ionization, Radiation dosimetry
Resumen

El objetivo de este proyecto fue caracterizar y calibrar el detector triple Multiplicador de Electrones Gaseoso (triple-GEM) que pertenece al grupo de investigación CRYOMAG de la Universidad Nacional de Colombia, al igual que determinar sus posibles aplicaciones en dosimetría médica. La respuesta del detector frente a varias fuentes de radiación fue caracterizada en términos de amplitud, duración, forma y polaridad de los pulsos, como también su eficiencia, ganancia, resolución de energía y resolución temporal. La proporcionalidad de energía del detector triple-GEM fue calibrada utilizando el espectro de una fuente radiactiva de hierro-55. Posteriormente, el detector fue utilizado para medir la dosis de radiación de esta fuente mediante cuatro métodos distintos, como también la dosis de una máquina de rayos X portátil a varios voltajes y corrientes del tubo. Las dosis obtenidas fueron comparadas con los valores de referencia.

Las propiedades características del detector fueron una resolución de energía del 19.5 %, una resolución temporal de al menos 40ns y una ganancia máxima de $5 \times 10^6$. Para las mediciones de dosis se encontró un coeficiente de calibración de $1.13 \times 10^4$ contra los valores de referencia de cada fuente de radiación. Se dio un buen acuerdo entre los cuatro métodos de medición de dosis que se utilizaron con la fuente de Fe-55. Se concluyó que el detector triple-GEM puede ser utilizado adecuadamente como un dosímetro, especialmente para aplicaciones en medicina nuclear.

Palabras clave: Detectores de partículas, Caracterización de detectores, Radiación cósmica, Radiactividad, Rayos X, Ionización, Dosimetría de radiaciones
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1 Introduction

Since the beginning of time, men have striven to understand the universe we live in. Tools and experiments that help us do so have been a great part of our history, and always will be. Currently, physicists use particle accelerators, colliders, and detectors to break down the world’s smallest components into even smaller, fundamental particles in a bet to understand the basic constituents of matter. These giant experiments allow us to study and observe the properties of particles and how they interact with each other according to the field of High Energy Physics. In order to do so, particles are smashed together at velocities almost equal to the speed of light, and the products of these collisions are recorded in specialized particle detectors that may give information about, for example, their charge, energy, trajectory, or momentum.

Possibly the most important of the aforementioned experiments is the Large Hadron Collider (LHC), a 27km-long tunnel that lies below the border between Switzerland and France. The LHC collides bunches of thousands of millions of protons with each other at four interaction points which are surrounded by a huge number of detectors, all put in place with the same objective: to identify as many products of the interaction as possible. This is why the LHC needs different types of detectors, like trackers, calorimeters, semiconductor detectors, ionizing chambers, and many others. For particles that are not stopped by calorimeters (such as muons), drift tubes, cathode strip chambers, and resistive plate chambers are used [73]. Cathode strip chambers operate as multi-wire proportional counters (MWPC), where muons interact with the particles of a gas mixture causing electron-ion pairs which, following an electric field, move close to a wire such that multiplication takes place [76]. The MWPC allows for energy proportionality, a good temporal resolution, and acceptable spatial resolution. However, this detector suffers rapid deterioration because of its fragility, and because of the discharge that the avalanche formation causes on the wires. As a consequence, molecule fragments are formed and polymerize into long chains of
molecules, which may attach to the electrodes further reducing the gas amplification \[37\].

Nonetheless, as Fabio Sauli demonstrated in 1996, wires can be avoided \[62\]. At that time, at CERN, he was developing the theory behind a Gas Electron Multiplier (GEM), in which the wires were replaced by micrometer-sized holes where their geometry would bend the electric field in such a way that an even better amplification could be achieved with respect to the MWPC. Permitting big sensitive areas without the rapid deterioration of the gas and the fragility of wire-based detectors, GEMs soon became the perfect solution to the issues of old ionizing chambers, which included single-wire proportional counters (SWPC), the MWPC, multi-step avalanche chambers (MSAC), ring imaging Cherenkov chambers (RICH), multi-drift modules (MDM), micro-strip gas chambers (MSGC), the MicroMegas detector, and resistive plate chambers (RPC) \[20\]. The GEM detector allows for notably less aging of the gas mixture after large bouts of radiation, a wide variety of applications, mass production, flexible geometry, low noise, fast electronic signal, and improved spatial and temporal resolution \[42\].

Since the early 2000s, there have been GEM detectors at multiple High Energy Physics facilities, such as the COMPASS, TOTEM, and LHCb experiments. Additionally, GEM-based detectors replaced other gaseous devices with a limited rate capability, such as the muon detectors at CMS and the end-caps of the time-projection chamber at ALICE, for neutron detection, fast tracking, and improved readout for large volume drift chambers \[20\]. They have also been proposed for the future International Linear Collider (ILC) and the STAR and PHENIX experiments at the Relativistic Heavy Ion Collider (RHIC).

The GEM detector was born at large High Energy Physics experiments, and it clearly continues thriving in that area. However, it has been shown that GEM detectors flourish well beyond their intended field, in areas such as medical imaging, radiology, astrophysics, structure analysis, among others. For example, it is now very common for academics and entrepreneurs to develop devices based on gaseous particle detectors for medical imaging with the currently used image generation techniques, such as CT, PET, SPECT, gamma-graphy, and radiology. Less work has been done to determine if gaseous ionizing detectors, such as the GEM detector, can be reliably used as dosimeters. Dosimetry is the area of medical physics that determines and measures the amount or dosage of radiation absorbed by a substance or living organism. Due to the great harm that can be caused in the
human body because of an excess of absorbed radiation, dosimeters are immensely important. However, they are usually quite costly, and most can only be read once every three months. The need for an affordable, big-sized dosimeter that can be read in real time sparked the interest of this project, that aims to characterize and calibrate a GEM detector, and determine if it can be applied to medical or nuclear dosimetry.

1.1. State of the art

1.1.1. Particle detectors

A particle detector is a high-precision device used to track, identify, and detect passing radiation, as well as its direction, energy transfer, and properties. At the present time, particle detection is done mostly using electronic methods that allow for better temporal, spatial, and energy resolution. Particle detectors have contributed significantly to the advances in science and technology. The development of detection techniques from cloud chambers and bubble chambers to Multi-Wire Proportional Chambers (MWPC), Resistive Plate Chambers (RPC), Micro Pattern Gaseous Detectors (MPGC), among others have been behind great discoveries. With these developments came multiple Nobel Prices, such as for the cloud chamber (1927), the Cherenkov effect (1958), the bubble chamber (1960), the MWPC (1992), and the detection of neutrinos (2002) [24].

In 1899, Antoine Henri Becquerel and JJ Thomson discovered that ions can be attracted to a conducting plate if an electric field is created in the air between them. This paved the way for the development of charged particle detectors that work according to this same principle. Some years later, Ernest Rutherford explained the nature of alpha, beta, and gamma radiation. With this understanding, devices were born that could detect particles using photographic plates, electroscopes, and ionization chambers. Yet these were only sensible to large amounts of radiation, and not individual rays.

In 1911 C.T.R Wilson built the first cloud chamber, which allowed the observation of the path followed by charged particles in an electromagnetic field. It kept being improved until 1930. Afterwards, the bubble chamber was invented in 1952 by Donald A. Glaser, for which he was awarded the 1960 Nobel Prize in Physics. In this new detector, the traces of particles can be seen in a liquid medium. It was a very important advance for the field of
In the 1930’s, Hans Geiger and Walther Müller (with some help from Rutherford) started implementing their knowledge of gas discharges to the fabrication of a device that could detect charged particles, that came to be known as the Geiger-Müller counter [24]. It was the first gas-based counter. It has been widely used ever since because of its simplicity, ease of handling, and low price. However, its major inconvenience is that it can’t measure the energy of incoming radiation (it has no energy resolution) [31].

The 40’s marked when gas detectors really started to become the norm. The Frisch-Grid Ionization Chamber was invented, and proportional counters that amplify charges in the gas were developed. Both of these started being used in spectroscopy, for alpha particles and for low energy X-rays [31]. However, in the 1950’s gas detectors were mostly replaced by semiconductor detectors for high-precision work.

The re-introduction of modern-era gaseous detectors started in the late sixties when Georges Charpak developed the MWPC. Its defining characteristic was that its electrodes were replaced by parallel wires to reduce the chances of having multiple dispersion, energy loss and secondary interactions. It had the best spatial resolution at the time, of only a couple hundred micrometers, allowing the localization of charged particles in two and three dimensions of incident radiation. It also had excellent energy resolution, and a big detection area. It was soon discovered that the MWPC could be used in high energy physics, particle physics, medical physics, crystal diffraction, and beta chromatography [31]. Since the 90’s, MWPC type detectors have been commonly used in radiology.

Because gaseous particle detectors had large sensitive areas, flexible geometries, simple and inexpensive fabrication processes, good spatial and temporal resolutions, and high counting rates, continuous work kept being done to develop new models. The RPC detector was made by R Santonico in 1981. He used bakelite electrodes separated by a gap and a mix of gases to achieve a temporal resolution of only 1ns [71]. Due to its unprecedented temporal resolution, ease of operation, and low cost of fabrication, this type of detector has been widely used in modern particle physics, such as in the construction of the muon detection system at the LHC, as well as at CERN’s SPS and LEP experiments, Fermilab, and SLAC [39]. With the latest advances, these detectors have made their way to many other applications, like medical imaging, calorimetry, Positron Emission Tomography (PET), and high energy physics [31].
1.1 State of the art

high speed tracking for minimally ionizing particles (MIPs) [24].

Afterwards, at modern high energy physics experiments, MPGDs were developed using recent advances in photolithography and microprocessing of electrical circuits [70]. These are simpler than MPWCs, more stable and more flexible. Examples of this type of detectors include the Gas Electron Multiplier (GEM), introduced by Fabio Sauli in 1997, the MICRO MEsh GAseous Structure (MICROMEGAS), the Resistive Micromegas, the Micropin Array, the Micro Wire Detector, and the Micro Pixel Chamber, among others [43, 32]. These detectors exhibit two dimensional spatial resolutions of 50µm or better, rate capabilities exceeding 1MHz/mm², gains above 10⁵, and very high detection efficiencies for MIPs [70]. Recent efforts with MPGDs have been focused on transferring these devices made for high energy physics experiments into other fields, particularly medical physics, through dosimetry and medical imaging devices.

New technological advances have allowed the improvement of the most important characteristics of detectors, such as their spatial and temporal resolution, speed, electronic noise and cost reduction. This has opened the door to the use of gaseous detectors in areas like astronomy, material science, medical physics, and many others. The most common detectors used at the present moment are pixel detectors, micropixel detectors, micropattern detectors, micro-strip detectors, parallel plate detectors, RPCs, and GEMs [61]. Most of these have been developed for a specific purpose, especially in the LHC experiments, be it tracking, particle identification, calorimetry, muon detection, etc.

At the moment, there are GEM-based tracking detectors at CERN’s LHCb, TOTEM, and COMPASS experiments. More recently, the gaseous muon detectors at CMS were replaced by GEMs, which allowed for neutron detection, faster tracking, and improvement in the readout of many drift chambers [20]. To prepare for the 2020 LHC upgrade in which the luminosity will be increased, the MWPCs used at the end-caps of the ALICE experiment’s time projection chambers (TPC) will be replaced by GEMs, whose mass production already started [50]. GEM detectors will also be used at the International Linear Collider (ILC), and the STAR and PHENIX experiments at the Relativistic Heavy Ion Collider (RHIC). Other proposals include a one meter long cylindrical GEM for the BESIII experiment at the Institute of High Energy Physics in Beijing [6], the use of GEM detectors inside of a magnet for trace reconstruction at the baryonic matter experiment
BM@N in Moscow’s NICA (Nuclotron-based Ion Collider fAcility) [48], and a TPC with GEM technology for the High Intensity Proton Accelerator J-PARC in Japan [47].

1.1.2. Applications in medical physics

The initial motivation for the use of particle detectors in medicine was the idea of replacing radiographic plates, in radiology, while trying to reduce the exposure time to patients. This would reduce the absorbed dose and its consequent side effects. Additionally, the possibility of storing images in a digital format would allow for reconstructions, composition, and off line management of images, therefore improving the diagnostic analysis and follow-up treatment [61]. This was the beginning of the technique now called CT (Computed Tomography). The first attempts at applying gaseous particle detectors to medicine date to the initiative suggested by Georges Charpak when he used MWPCs in X-ray radiology [22]. Fabio Sauli then presented an analysis of the advantages of using MWPCs in radiology and in coronary angiography, which has had good results in the detection of synchrotron radiation [63]. GEM detectors have been used successfully to obtain live images of a tumor, using therapeutic gamma ray beams and X-rays. This information can be fed back to the beam to control the treatment in a more efficient way [58]. Additionally, the same type of detectors has been used in clinical images with the mixed technique called SPECT (Single Photon Emitted Computed Tomography) and CT. The high energy and spatial resolution of GEMs helps in the detection of radioactive tracers in small volumes of mass, allowing the identification of cancerous cells with greater efficacy [5]. A microstrip type detector was also successfully tested to provide X-ray images in nuclear medicine [38]. Micropattern detectors were used by a Swedish research group in a monitoring system that permitted the simultaneous visualization of the therapeutic radiation beam and the tumor using X-rays [30]. Recently, Sauli’s group at CERN was developing similar GEM detectors for applications in PET (Positron Emission Tomography) [26].

All of these applications and results demonstrate how feasible it is to develop devices based on gaseous particle detectors for medical imaging with the currently used image generation techniques (CT, PET, SPECT, gammagraphy, RX radiology, etc.). There are now many institutions and businesses dedicated to the development of commercial products for hospitals based on these detectors. However, there is a lot less information about clinical
1.2 Motivation

Beyond High Energy Physics, applications of GEM detectors in medical imaging, astrophysics, structure analysis, and others have also been studied [20, 75]. A unique feature of GEM detectors is that the place where the amplification takes place is electrically separated from the readout plane, which allows a wide freedom in the choice of readout pattern. These can be made using strips or pads, all at ground potential [16]. As only the electron charge component of the avalanche is detected, the signal is very fast. Several GEM foils can be cascaded, permitting large gains even in the presence of heavily ionizing particles, which usually induce discharges in most counters. Thanks to their flexible geometry and large detection areas, many researchers have seen the benefits of using GEMs to detect ionizing radiation used in radiotherapy or radiology [11, 36, 64]. Past research shows that because it is relatively inexpensive and has a very good amplification factor at low voltages, it might be the perfect detector for medical dosimetry. However, the first steps needed to be taken in order to make sure that these detectors that were made for huge High Energy Physics experiments would actually work well at the much lower energies used in this particular application. For this purpose, a triple-GEM detector was acquired by the CRYOMAG research group at Universidad Nacional. It was then necessary to characterize,
test, and calibrate it, and to determine the possible adjustments that should be made to that triple-GEM detector to make it ideal for medical dosimetry.

In this project, both a theoretical and an experimental understanding of the functioning and characteristics of a triple-GEM detector were gained. The necessary changes were made to the detector so that it could be properly operated and read, including physical adjustments, functionality tests, and calibrations. Additionally, several important properties of its detection were characterized to determine its range of operation. With this information, it was possible to study its potential applications.

These findings opened the door to applications with a social impact, like the possibility of using the triple-GEM as a radiation dosimeter in medical physics. Since it is less expensive than currently used detectors, we expect that, if this detector works for medical dosimetry purposes, it can give hospitals all over the world a chance to use treatments and imaging technology that requires the precise dosimetry of radiation, even those with a low budget. This can spread the use of cutting-edge radiology and radiotherapy in our country and beyond.

Apart from the discovered dosimetry applications in medical physics, the development of this project certainly had an academic impact. Understanding GEM detectors gave insight into other types of detectors, and furthered the field of particle detector physics in our university. Judging from the countless applications of detectors in our society, that was greatly beneficial. All of this was the motivation behind this project.

1.2.1. Clinical importance of radiation detectors

The most common reason why the general public gets irradiated is because of X-rays from medical imaging. Every time someone goes for a diagnostic radiology image, or a routine exam, they receive a certain dose of radiation. The excess of dose can lead to many short and long term effects including cancer. Therefore, it is very important to monitor and prevent the accumulation of radiation dose. This means that radiation and dose detectors, called dosimeters, are extremely valuable and necessary to prevent diseases.

Radiation detectors are also used in radiotherapy. Radiotherapy is a treatment method for different illnesses that uses ionizing radiation such as X-rays, gamma rays, electrons, protons, and alpha particles [61]. It has been used as treatment for more than a century.
The first known success of healing due to radiotherapy dates back to 1899 \cite{2}, just four years after Roentgen discovered X-rays in 1895. Since then, the implementation of linear accelerators in 1953 and the use of Cobalt-60 are the two major improvements to the field \cite{9}.

Advancements in the area of radiotherapy are aiming to reduce the toxicity of the radiation to organs close to tumors, using dosimetry quality controls in radiotherapy equipment. This is where radiation detectors become essential to guarantee that the patient is receiving the planned dose and to protect occupationally-exposed personnel. Ionizing radiation detectors allow radiotherapy to be a safe procedure in clinical setting for all involved parties.

1.3. Objectives

1.3.1. General objective

The general objective of this project was to characterize, calibrate, and test the different properties of a triple-GEM detector using various sources of radiation, and to determine how to best adapt it for medical dosimetry.

1.3.2. Specific objectives

1. To make preliminary adjustments to the triple-GEM detector regarding the high voltage supply and pick-up signal circuits as needed

2. To characterize typical signals for cosmic rays in terms of amplitude, duration, and shape, and to measure gain, efficiency, sensitivity, and energy resolution

3. To calibrate the triple-GEM detector with respect to the spectrum of a known radioactive source

4. To study the requirements and modifications needed to adapt the detector for medical dosimetry
2 Theoretical Background

2.1. Cosmic radiation

The Earth is constantly being bombarded by high energy rays of particles that come from outer space. Primary cosmic rays come from black holes, supernovas, and pulsars. They are made up of 86% protons, 10% alpha particles, 2% electrons, 1% heavy nuclei (from Li to Ni), and 1% gamma rays and neutrinos. Their energy ranges from $10^{11}$ to $10^{21}$ eV. When these primary cosmic rays interact with the atoms of the atmosphere, they produce secondary cosmic rays. These are made up of electromagnetic particles (electrons, positrons, photons), hadrons (protons, neutrons, pions, kaons), and muons. At sea level, the composition is approximately 72% muons, 15% photons, and 9% neutrons. The intensity is proportional to the angle ($I = 0.65 \cos^2 \theta$). This gives about $1.36 \pm 0.06$ muons per minute per square centimeter, with an energy of about 4GeV.

As a source of elementary particles, cosmic rays have two advantages: they come at no cost and their energy is huge, a lot bigger than what can be produced at a laboratory [40]. This makes them a very good source of ionizing radiation to test detectors with. But they also have two important disadvantages: the velocity at which they hit detectors is very small, and they are completely uncontrollable.

However, cosmic rays are a very powerful source of muons. Muons are charged leptons (fermions, spin 1/2) that decay to form electrons ($\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$) or positrons ($\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$). They have a mass of 105.66 MeV/c$^2$, a charge of $-e = -1.602 \times 10^{-19}$C, and a half-life of 2.197µs. Even with their very short life-time, they are the most abundant energetic particles at sea level because they travel at almost the speed of light [31]. Muons interact with matter by ionizing it, losing their energy by interacting with the electrons of the atoms. The loss of energy of muons that cross the atmosphere is proportional to the
Theoretical Background

2.2. Interaction of radiation with matter

The triple-GEM detector works thanks to the principles of the interaction between radiation and matter. When radiation particles come into the vicinity of particles of matter, they interact in ways that depend on the type of incident particle and its energy.
Photon interactions

Photons can interact with either the electrons of atomic shells, the nuclei, or the atoms themselves. If the energy of an incident photon is greater than (or equal to) the ionization energy of an electron bound to one of the material’s atoms, this electron will be expelled from the atom in a process called ionization. If there is leftover energy, it will transform into kinetic energy of the now free electron. Therefore, if ionizing radiation hits matter, free electrons will be produced. If non-ionizing radiation hits matter, there won’t be any freed electrons, and the effect might only be noticeable through heating.

The two categories of interactions between photons and matter are absorption interactions, in which the photon gives up its energy to the matter completely, and scattering, in which the photon only changes direction and possibly gives part of its energy to the matter. The first category includes the photoelectric effect and pair production, while the second includes Rayleigh and Compton scattering [57].

Therefore, photons may undergo one of four interactions with the atoms of a material: photoelectric absorption, coherent (Rayleigh) scattering, incoherent (Compton) scattering, or pair production [45]. The number of photons that remain after crossing a certain distance decreases exponentially due to these interactions. Which interaction actually occurs when a photon crosses through matter depends on the cross section, which in turn depends on both the energy of the incident photon and the properties of the material. Therefore, the cross section is determined by the atomic number of the medium $Z$ and the energy of the incident photon $E_\gamma$. Cross section is defined as the probability of a specific interaction taking place; in the interaction of two particles, the cross section is the area transverse to their relative motion in which they will scatter off each other. The total cross section is the differential cross section integrated over all scattering angles. The numerical values of cross sections are theoretical or semi-empirical, and the greater they are the more probable it is for a specific interaction to occur (see Fig. 2-2).

The photoelectric effect occurs when an incident photon interacts with a tightly bound electron, whose binding energy is similar to (but not greater than) the photon’s energy. As a result, the photon disappears and the bound electron is ejected with a kinetic energy equal to the photon’s energy minus the electron’s binding energy [77]. The greatest cross section occurs with the K-shell, followed by the L-shell and outer shells. The atom is left in an
Theoretical Background

Figure 2-2: Cross sections of the four main types of interactions between photons and matter: photoelectric absorption, coherent scattering, incoherent scattering, and pair production. The higher the cross section, the more probable it is for a specific interaction to take place. At lower energies, most photons interact via the photoelectric effect. At MeV energies, Compton effect is the most prominent, while pair production only occurs at higher energies [14]. Therefore, in the energy range of radioactivity, the photoelectric effect and the Compton effect are the main mechanisms in which photons interact with matter.

Excited state, so an electron from a higher shell will fill the vacancy left in the inner shell. In this process, a characteristic fluorescent photon or an Auger electron is emitted (see Fig. 2-3). The peaks in the photoelectric cross section occur when the incident photon’s energy is equal to the binding energy of electrons from a specific inner shell [57]. Therefore, the location of these peaks will be determined by each material’s ionization energies. The photoelectric absorption cross section per atom \( \sigma_{pe} \) is proportional to \( Z^4 / E_\gamma^3 \). This implies that as the incident photon’s energy increases, the less probable it is for it to interact via the photoelectric effect with a medium.

The Compton effect happens when an incident photon interacts with an electron whose binding energy is much smaller than the photon’s energy (outer shell electron), such that the binding energy of the electron can be neglected and the electron can be considered free
Figure 2-3: Depiction of the photoelectric effect: an incident photon interacts with a tightly bound electron. The photon disappears and the electron is ejected from the atom. Afterwards, an Auger electron is emitted to return the atom to its ground state [3].

The Compton effect is then the scattering of an incident photon off of an outer shell electron, which is taken to be initially at rest (see Fig. 2-4). Part of the photon’s energy is transferred to the electron, which is then ejected from the atom with kinetic energy $E_C = h\nu - h\nu'$ (because of the law of conservation of energy). It is therefore called recoil electron, or Compton electron.

The complete differential cross section per electron for the Compton effect is given by the Klein-Nishina formula:

$$d\sigma = d\omega' \frac{m}{\omega^2} \pi r_e^2 \left[ \frac{\omega}{\omega'} + \frac{\omega'}{\omega} + \left( \frac{m}{\omega'} - \frac{m}{\omega} \right)^2 - 2m \left( \frac{1}{\omega'} - \frac{1}{\omega} \right) \right]$$

(2-1)

where $m$ is the mass of the electron, $r_e$ is the classical electron radius, $\omega$ is the frequency of the incident photon and $\omega'$ the frequency of the scattered photon. The Compton cross section $\sigma_C$ is proportional to $Z$.

Rayleigh scattering, also called coherent scattering, can be seen as a special case of Compton scattering. In the case of Rayleigh scattering, no energy is transferred between
Figure 2-4: Depiction of Compton scattering: an incident photon scatters off an outer shell electron (initially at rest), transferring some of its energy to it. The electron recoils away with energy $E_C = h\nu - h\nu'$ [57].

the incident photon and the bound orbital electrons because their binding energy is too high compared to the photon’s energy. Therefore, virtually no energy is transferred to the electron, and the photon merely suffers a change of direction but keeps its incident energy. This causes Rayleigh scattering to have no effect on the transfer of energy, but it does contribute to the attenuation of incident rays.

The Rayleigh cross section $\sigma_R$ is proportional to $Z^2/E^2_\gamma$. Therefore, in heavier atoms, where the electrons are more tightly bound, Rayleigh scattering is relatively more common than Compton scattering. Additionally, Rayleigh scattering has been proven to be more prominent at small incidence angles, and negligible for angles larger than 60 degrees [57].

Finally, pair production is the process in which a photon in matter disappears and leaves behind an electron-positron pair (see Fig. 2-5). This reaction can’t occur in a vacuum because momentum would not be conserved in this case. In matter, the Coulomb nuclear field can take the recoil momentum [57]. The photon is required to have an energy greater than twice the rest mass of an electron ($E_\gamma > 2m_e c^2$), so that it can form the two masses. Because the recoil of the nucleus can be neglected, the kinetic energy of the electron-positron pair is that of the incident photon minus twice the rest mass (511 keV): $E_- + E_+ = h\nu - 2m_e c^2$. The pair production cross section $\sigma_{pp}$ is proportional to $Z^2$. If the photon’s energy is more than four times the electron’s rest mass, a type of pair production called triplet production might occur close to an orbital electron. The three particles that result
are an electron, a positron, and the orbital (recoil) electron \[77\]. This electron receives a noticeable amount of energy, so the minimum energy that the incident photon must have in order for triplet production to occur is \(4m_ec^2\).

![Diagram](image)

**Figure 2-5:** Depiction of pair production: a photon in the vicinity of a nucleus vanishes, leaving behind an electron and a positron which scatter off in different directions.

The total cross section \(\sigma\) is the sum of the cross sections per atom of the individual interactions, generally ignoring triplet production and photomuclear reactions. The Compton scattering cross section is per electron, because the photon interacts with all the electrons in the atom \[57\]. Therefore, it needs to be multiplied by the atomic number to get the cross section per atom. This gives the following total cross section per atom:

\[
\sigma = \sigma_{pe} + \sigma_R + Z\sigma_C + \sigma_{pp}
\]  

(2-2)

**Electron and positron interactions**

When charged particles cross through a medium, they interact with it via the Coulomb force with both the nucleus and the orbital electrons of its atoms. Incident charged particles lose their energy gradually, in small portions as they collide with other particles, so they have a finite range in matter \[57\]. This is called the Continuous Slowing Down Approximation, or CSDA. Because charged particles typically undergo a very large number of interactions, their range in a specific medium can be determined. This is called the CSDA
range, or $R_{\text{CSDA}}$ [9].

Collisions between particles are considered elastic when only a change in direction occurs, and inelastic when there is an additional transfer of energy [77]. The former occurs when the incident electron scatters from the nucleus, exciting the atom, while the latter occurs when the incident electron interacts with the atom’s valence electrons, causing ionization.

The total energy loss per unit length is described by the stopping power $S$:

$$S = \left( \frac{dE}{dx} \right)_{\text{total}} = \left( \frac{dE}{dx} \right)_{\text{coll}} + \left( \frac{dE}{dx} \right)_{\text{rad}} \quad (2-3)$$

which is divided into the following terms:

- **Soft collision**: if the interaction of the incoming charged particle with the atom is soft, virtually none or only a very small amount of its energy is lost. The incoming particle’s Coulomb force affects the whole atom, which receives some energy. It can be excited to a higher energy level or become an ion if one of its valence electrons gets pulled off. This is the most common type of interaction, accounting for about half of the energy transferred to the medium [9].

- **Hard or knock-on collision (electronic interaction)**: in this case the incoming charged particle interacts with a single orbital electron of the medium’s atoms. This is followed by the ejection of the orbital electron (which was considered free) or the excitation of the atom. Ejected electrons that have enough energy to continue travelling and ionizing more atoms are called $\delta$ or knock-on electrons, which dissipate energy along its path. When the excited atom returns to its ground state, it will emit its characteristic X-rays or Auger electrons. The absorbed dose, of vital importance in dosimetry, is directly proportional only to the collision stopping power.

- **Radiative interaction (Coulomb interaction with the nuclear field)**: when the incoming charged particle interacts with the absorber atom’s nucleus. This results in elastic scattering almost every time (with no energy loss) or sometimes a big energy loss by the production of radiative photons (Bremsstrahlung). These radiative photons travel far before being absorbed. Radiative interaction mostly happens for electrons hitting materials with a high atomic number.
Which interaction occurs is determined by the impact parameter $b$, which is defined as the perpendicular distance between the path of the incident particle and the center of the nucleus it is approaching, in relation to the classical atomic radius $a$. When $b \gg a$, the collision is soft. When $b \sim a$ the collision is hard, or knock-on. And when $b \ll a$, the interaction is radiative. This means that ionization losses decrease logarithmically with the incident particle’s energy, and increase linearly with the material’s atomic number $Z$. This relation can be verified with the Bethe-Bloch equation, which describes the mass stopping power. Mass stopping power is generally preferred over the stopping power, and is written as $S/\rho$ where $\rho$ is the medium’s density. As defined by the International Commission on Radiation Units (ICRU) Report No. 37, the mass collisional stopping power is given by:

$$\frac{S_{\text{col}}}{\rho} = \frac{2\pi r_e^2 mc^2}{u} \frac{1}{\beta^2 A} \left[ \ln \left(1 + \frac{\tau}{2}\right) + F^{\pm}(\tau) - \delta \right]$$  \hspace{1cm} (2-4)

where $r_e$ is the classical electron radius, $m$ is the mass of an electron, $c$ is the speed of light, $\beta$ is the ratio of the particle’s velocity to the speed of light, $u$ is the atomic mass, $Z$ the atomic number, $A$ the atomic weight, $F^{\pm}(\tau)$ is an auxiliary function for electrons (-) and positrons (+) (due to the fact that for electrons, large energy transfers of the stopping power are governed by the Møller (1932) cross section, while for positrons, large energy transfers are governed by the Bhabha (1936) cross section [65]), $\tau$ is the ratio of kinetic energy of the electron to its rest energy, and $\delta$ is a correction factor for the density effect [77] (which reduces the collisional stopping power due to the polarization of the medium caused by fast electrons).

**Range of electrons**

The range of an electron depends on the individual interactions that it has with the medium. One analytical way to estimate the range is through the “Continuous Slowing Down Approximation” (CSDA), in which the range $R_{\text{CSDA}}$ is calculated by integrating the inverse of the mass stopping power:

$$R = R_{\text{CSDA}} = \int_0^{E_0} \left(\frac{\rho}{S}\right)dE = -\int_0^{E_0} \left(\frac{dx}{dE}\right)dE$$  \hspace{1cm} (2-5)

The actual range of the electrons will usually be smaller, since they experience the creation of secondary particles along their path that makes them lose part of their energy.
The depth of penetration will be even less because electrons scattered in a medium have curved trajectories \[77\].

![Figure 2-6: CSDA range of electrons, protons, and alpha particles in argon gas (values from NIST).](image)

### 2.3. Classifying particle detectors

One way of classifying particle detectors is into the three following groups:

- **Electric detectors:** The electrons emitted by the ionizations inside the detector are accelerated by an electric potential, which gives them enough energy to generate ionizations themselves. This creates an avalanche of multiplication, which amplifies the signal (see Sec \[2.5.3\]). If the medium inside the detector is a gas, the ionizations of the gas molecules occur due to discharges in it. These detectors include ionization chambers, proportional counters, Geiger-Müller tubes, etc. Gaseous detectors collect the electric charge generated by the particle along its track \[25\]. This can provide information on the location, trajectory, and energy of the incoming particle. In crystal
detectors, the signal is determined by the electron-hole pairs created along the path of the incoming particle.

- Cherenkov detectors and Scintillation counters: Incident charged particles excite the atoms in the medium. When the excited atoms go back to their base state, they emit light. This light is then converted via the photoelectric effect into an electric pulse and amplified using a photomultiplier tube.

- Trace detectors: The trajectory of the particle is visible to the human eye due to the nature of the interaction between the particle and the medium. Examples of this type of detectors include bubble chambers, cloud chambers, spark chambers, and emulsion detectors. These are mostly obsolete.

Different detectors are needed depending on the type of particle and the energy range that one wants to detect. This is the case because different particles interact in different ways. Since neutral particles can’t produce an electric signal directly, it is necessary to make them interact with the medium in a way that produces charged secondary particles, through which the characteristics of the incident neutral particle can then be reconstructed. As was seen in the previous section, photons interact through the Electromagnetic interaction in the form of Compton Effect, Photoelectric Effect, or Pair Production. Neutrons interact through the Strong interaction, like in the elastic collision $np \rightarrow np$. Neutrinos interact through the Weak interaction, but they are only noticeable if there is a strong flux since the probabilities of interaction are very small.

Detectors can provide information on many characteristics of incident particles. Some detectors give information on some characteristics, and others on other characteristics. These may include counting (to measure the activity of radioactive sources), identification (determining the mass of the incident particles), energy (measuring the range of particles or the energy left in the detector), cross section (measuring the interaction distances in trace detectors), direction, velocity, and flux [43].

2.4. Characteristic properties of detectors

There is no universal particle detector; for each type of particle in a certain energy range there is an optimal detector. There are certain characteristic properties of detectors
that one should study when trying to pick the best one. This analysis is called *characterization*. Characterizing a detector means to determine the values and behavior of its different properties, in order to understand its range of functionality. These properties include sensitivity, response, energy resolution, temporal resolution, efficiency, gain, and response to various sources.

### 2.4.1. Sensitivity

The sensitivity of a detector is its ability to produce a signal that can be measured for a certain type of radiation of a certain energy [25]. This characteristic is the most fundamental of all since it allows to determine which type of detector works best for each type of radiation. There is no single detector that is sensitive to all types of radiation at all energies. A detector is designed to produce a signal for only the specific particles and energies that interact with it [49]. This is the detector’s sensitivity, and depends on the probability of an incoming particle depositing some or all of its energy in it (cross section), the noise level, and the properties of the material that surrounds its sensitive volume [41].

The cross section and the mass of the detector determine the probability of an incident particle interacting with the medium inside the detector. Low-mass detectors will detect only a small part of the energy and won’t be very sensitive to neutral particles. The minimum detectable signal will be determined by the medium and the noise of both the detector and the electronics [35]. The noise can be seen as the fluctuating voltage or current that is always present in the detector’s output signal, even when there is no incident radiation. The ionization signal, on the other hand, is much larger than the noise. For a type of radiation at a certain energy, the number of ionizations produced by an incident particle also depends on the properties of the detector’s sensitive volume. The thickness of the material, for example, determines the minimum energy the incident particle must have in order to penetrate completely and be detected [49].

### 2.4.2. Response

Apart from detecting the presence of radiation, most detectors can also determine the energy of this radiation. If a detector completely absorbs radiation, the number of ionizations inside it can give an estimate of the energy deposited by that incident radiation.
Detectors that can measure energy are spectrometers.

In general, the output signal of an electric detector is a current pulse. The number of ionizations is directly proportional to the total charge inside of this signal. Therefore the energy can be determined by integrating the pulse with respect to time. If the shape of the pulse doesn’t vary greatly between events, this integral is proportional to the amplitude of the signal pulse [49] (but only when the signal has been preamplified with a charge preamplifier), so this characteristic is of great interest in detector experiments.

The ratio between the energy of an incident particle and the total charge of the output signal it generates is what is called the response of the detector [24]. This relation should be linear, but that is not always the case. Most detectors have a set energy range at which their response is linear.

If a particle loses an amount of energy $E_{\text{rad}}$ when crossing a detector, then the detector’s response $r$ is defined as

$$ r = \frac{E_{\text{rad}}}{V} \quad \text{or} \quad r = \frac{E_{\text{rad}}}{Q} $$

(2-6)

where $V$ or $Q$ is the preamplified signal of the detector, given by a voltage or a charge [41].

### 2.4.3. Energy resolution

The energy resolution of a detector determines how close two incident energies can be and still be distinguished as different. In the resultant spectrum, what is usually observed is a Gaussian peak with a set width, that depends on the fluctuations on the number of ionizations and excitations produced.

The energy resolution can be computed from the position of the characteristic peak $\mu$ of the measured radiation spectrum, along with its Full Width at Half Maximum (FWHM) [28]. This calculation can be done for different detector voltages by fitting the curve and determining both $\mu$ and $\sigma$. 
The energy resolution $R$ is then given by:

$$R = \frac{\text{FWHM}}{\mu} = \frac{\Delta E}{E} \tag{2-7}$$

This means that a detector will have infinite different energy resolutions depending on the energy at which it is being put to work, since at different energy ranges the interaction methods vary. Therefore, the energy resolution greatly depends on the energy deposited by the incident radiation inside the detector [49].

For thin detectors (in which the loss of energy per unit distance $dE/dx$ is small), the number of ionizations $N$ is small, so Poisson statistics can be used. Then, if $N = E/w$ where $w$ is the energy needed to create a pair $e^-X^+$, we get that $\sigma^2 = N$. This means that the energy resolution is given by the statistical error over the value of $N$:

$$R = \frac{\Delta E}{E} = 2.35 \sqrt{\frac{N}{N}} = 2.35 \sqrt{\frac{w}{E}} \tag{2-8}$$

since FWHM $= 2\sqrt{2 \ln 2} \sigma = 2.35\sigma$.

If the particle loses all its energy, then there are no longer fluctuations of $dE/dx$ because the total energy deposited is now constant. So the maximum number of ionizations that can occur and the energy lost per ionization depend on this number.

This difference can be accounted for using the Fano factor $F$, such that $\sigma^2 = FN$. The Fano factor is a function of all the elementary processes that can cause a transference of energy into the detector, and those that can’t, such as photon excitation. The formula for
the energy resolution now becomes:

\[ R = 2.35 \sqrt[2]{\frac{Fw}{E}} \]  \hspace{1cm} (2-9)

For gases, \( F \leq 0.01 \), so they usually have a good energy resolution, while for scintillators \( F \approx 1 \), so they are similar to a Poisson distribution.

Apart from the fluctuation in number of ionizations, a number of external factors can affect the global energy resolution, such as electronic noise [35]. The total energy resolution is therefore given by:

\[ (\Delta E_{total})^2 = (\Delta E_{detector})^2 + (\Delta E_{electronic})^2 + \ldots \]  \hspace{1cm} (2-10)

### 2.4.4. Temporal resolution

The characteristic time of a detector, or response time, is how long you need to wait for a signal to be registered after a particle passes through. In other words, it’s the time needed for a signal to be recorded. Time resolution is the spread in arrival times of the signal charges onto the anode. This depends on the distribution of primary ionization clusters in the drift volume, the drift velocity and diffusion of the electrons in the gas, the size of the detector, and its physical mechanism. Sensitive time is how long it takes for the detector itself to be ready. It is determined by the rise time of the electric pulse signal, which is the time needed for the pulse to go up from 10\% to 90\% of its height. The duration of the signal is also important since a second event can’t be detected during this period, either because the detector is not sensible to it or because the second signal is obscured by the first. This is part of the detector’s dead time and puts a limit on the count rate at which it can function correctly [34].

The temporal resolution can be calculated by measuring the number of counts for a fixed exposure time, and calculating the time per count for sources of different levels of activity [27]. The number of counts should increase linearly with the source’s activity, but a real detector will reach a point of saturation where the number of counts will remain constant for an increasing activity. This behavior helps determine the temporal resolution of the detector. This can also be done with an X-ray source, by varying the flux for different voltages and determining the point of saturation.
2.4.5. Efficiency

The efficiency of a detector is the probability that a particle that crosses through it is detected. It is defined as the ratio between the number of detected particles and the number of incident particles.

There are many factors that can affect a detector’s efficiency. Some of the most important include the type and energy of the incident radiation. The relative efficiency of a detector is very different while detecting alphas to betas, gammas, or neutrons, because of the different interaction mechanisms that each has with the sensitive material in the detector. The energy of alphas or betas will also determine if they will be able to have a long enough range to be detected. The energy of gammas will determine the absorption coefficient for the specific interaction process taking place.

Other characteristics that affect the efficiency of a detector are the electric coupling of the detector to the circuit, the discrimination level to eliminate electronic noise, the values and precision of the necessary voltages, the magnitude of the amplification of the pulses, the sensitivity of the detector, and the precision of the measuring devices.

The total or absolute efficiency is defined as:

$$
\epsilon_{abs} = \frac{\text{Registered events}}{\text{Total events emitted by the source}} \approx \epsilon_{int} \cdot \epsilon_{geo}
$$

(2-11)

where $\epsilon_{int}$ is the intrinsic efficiency, or the probability the radiation interacts with the
2.4 Characteristic properties of detectors

detector (this is the most common efficiency mentioned during the characterization of a
detector):\[\epsilon_{\text{int}} = \frac{\text{Registered events}}{\text{Events that reach the detector}}\quad (2-12)\]

and $\epsilon_{\text{geo}}$ is the geometric efficiency, which depends on the size and geometric confi-
guration of the detector and its distance to the radiation source, as well as the angular
distribution of the incident radiation \[24\]:\[\epsilon_{\text{geo}} = \frac{\text{Events that reach the detector}}{\text{Total events emitted by the source}}\quad (2-13)\]

![Diagram of the geometric conditions of a detector that determine its geometric
efficiency](image)

**Figure 2-9:** Diagram of the geometric conditions of a detector that determine its geometric
efficiency

However, determining absolute efficiencies is usually a very complex matter, since there
is really no way of knowing the exact number of particles that leave a source and reach
the detector. It is more usual to see relative efficiencies, for which it is necessary to have a
standard to compare the values to \[52\]. This standard can be a comparison with a reference
detector.

\[\epsilon_{\text{rel}} = \frac{\text{Absolute efficiency}}{\text{Standard}}\quad (2-14)\]

The relative efficiency can be calculated by setting up a telescopic arrangement with a
scintillator on each side of the detector. Both scintillators are connected through an AND
gate, which sends a signal if and only if both scintillators detect a particle. Then this signal
is connected to the detector through another AND gate, which sends a signal if and only if
the particle was also detected by the detector. The percent of matches will determine the
efficiency.
Additionally, intrinsic efficiency can be calculated by comparing the number of counts in a fixed time with the theoretical number of incident particles. For muons, for example, one expects about $1.87$ hits per minute per cm$^2$, multiplied by the detector’s active area (because of Bogota’s altitude). The net efficiency takes into account absolute, intrinsic, and geometric efficiency.

### 2.4.6. Gain

The gain is defined as the ratio between the charge measured at the readout anode and the charge generated by the incident particle \[G\]. It is proportional to the readout current $I_{\text{readout}}$, and inversely proportional to the number of primary electrons generated per ionization $n$ and the maximum activity measured in counts per second $f$, which are both constants for a given source, gas, and detector \[4, 19\]. The gain can then be computed using a constant source of monochromatic photons, such as an X-ray tube or a radioactive source, and determining the readout current due to the source. This readout current is the current from all the strips connected in parallel, and it is calculated as the current with the source minus the current without the source \[54\]. It is then compared to the total primary charge: $n_{\text{primary}} \times e$.

\[
G = \frac{I_{\text{readout}}}{f \times n_{\text{primary}} \times e} \quad (2-15)
\]
In this equation, $e$ is the electronic charge and $n$ can be determined from the average energy of the ionizing radiation source over the energy required to generate an electron-ion pair in the gas mix.

### 2.4.7. Response to various sources

The characterization of a detector also includes detecting different radiation sources and determining if the obtained response looks like what is expected for each one. It is common to use radioactive sources who’s spectra are well known, so that the functionality of the detector can be evaluated. For example, the spectrum of a decaying radioactive source has a characteristic peak, while the spectrum of cosmic rays falls with energy. So to characterize a detector, the amplitude, duration, shape, and polarity of pulses can be determined, as well as the size of the background noise, the characteristic curve, and the range of operation before sparks are generated.

### 2.5. Gaseous ionizing detectors

Ionizing detectors were some of the first electronic devices developed to detect radiation. These devices work thanks to the direct recollection of charges released through ionizations as a particle passes through a gas. Gases are used because the velocity of electrons and ions is a lot greater in a gas, making the recollection faster. There are three types of gaseous ionizing detectors: ionization chambers, proportional counters, and Geiger-Müller counters. These three radiation detection devices work according to the same principle. They are inside a gas-filled container, with the thinnest walls possible (to not interfere with the incoming radiation), to which a voltage difference is applied. This generates a radial electric field inside:

$$E = \frac{1}{r \ln b/a} \frac{V_0}{r}$$  \hspace{1cm} (2-16)

Therefore, when radiation crosses the container, a number of electron-ion pairs (proportional to the energy of the incident radiation) will be created. These are called primary
ionizations. Thanks to the force exerted on them by the electric field, positive ions will be accelerated towards the cathode and electrons towards the anode, where they will be collected (see Sec 2.5.2). In this process, the primary charges may gain enough energy to produce secondary ionizations (see Sec 2.5.3). All of the resulting electrons will make up the final signal, which is proportional to the intensity of the electric field and the energy of the incident radiation [46].

Figure 2-11: Inside of a gaseous ionizing detector. Under the influence of an electric field, electrons and positive ions drift towards opposite electrodes [24].

The number of ions generated by the gas can be calculated through the following relation [31]:

$$n_{\text{total}} = \frac{\Delta E}{W_i}$$  \hspace{1cm} (2-17)

where $n_{\text{total}}$ is the number of electron-ion pairs generated, $\Delta E$ is the total energy loss and $W_i$ the ratio of energy loss and number of ions. This is also equal to the Poisson distribution given by:

$$\bar{n} = \frac{L}{\lambda} = LN\sigma_i$$  \hspace{1cm} (2-18)

where $\bar{n}$ is the average number of electron-ion pairs generated, $L$ is the length of the trajectory of the incident radiation within the gas, $\lambda$ the mean free path, $N$ the number of atoms in the length $L$, and $\sigma_i$ the probability of producing an ionization in gas $i$ per unit length.

This all leads to the efficiency of detection being limited by the following [31]:
2.5 Gaseous ionizing detectors

\[ \epsilon_{\text{det}} = 1 - P(0) = 1 - e^{-n} \] (2-19)

This relation shows that the greater the number of electron-ion pairs generated, the greater the efficiency of detection.

2.5.1. Ionization of gas particles

Ionization is one of the most important ways in which radiation transfers energy to a medium. It is defined as “the process by which electrically neutral atoms or molecules are converted to electrically charged atoms or molecules (ions)” [17]. When a charged particle travels through a gaseous medium it ionizes its atoms through the Coulomb interaction, therefore releasing free electrons and leaving behind positive ions. Photons can also ionize atoms via the Photoelectric effect if they are energetic enough. If the ejected electrons have enough energy, they may cause even more ionizations, called secondary ionizations [17].

For most gases, the minimum ionization energy ranges between 10 and 20eV, but the average energy required to generate an ionization is twice as big. This is the case because the energy transferred to the electron is usually greater than the ionization energy, and some of the extra energy is absorbed by the electron as kinetic energy or released as heat. For ionization to take place in a detector, it needs to be filled with a gas or a mixture of gases. Any gas can be used, including air, but the most common is a mixture of a noble gas such as argon with an organic gas (see Sec 2.5.5).

2.5.2. Diffusion of ions and electrons in the gas

The movement of ions and electrons inside the detector is described by the kinetic theory of gases, which talks about both diffusion and drift (in the presence of an electric field).

Diffusion describes when, in the absence of an electric field, ions and electrons generated from the ionizations caused by incident radiation spread uniformly away from their creation point. During their trajectory they collide multiple times with the molecules of the gas and deposit their energy along the way, finally recombing with an ion.
At thermal energies, the velocities of charges are defined by Maxwell’s distribution, which states that the average velocity is given by 

\[ v = \sqrt{\frac{8kT}{\pi m}} \]  

(2-20)

where \( k \) is Boltzmann’s constant, \( T \) the temperature, and \( m \) the mass of the particle. This implies that the average velocity of electrons is a lot greater than that of ions, since ions are so much more massive. At room temperature, the velocity of the electron is in the order of \( 10^6 \) cm/s, while that of positive ions is around \( 10^4 \) cm/s. From the kinetic theory of gases, the linear distribution of charges after diffusion has occurred for a time \( t \) is given by the following Gaussian distribution:

\[ \frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} e^{-\frac{x^2}{4Dt}} \]  

(2-21)

where \( N \) is the number of charges, \( x \) is the distance from the creation point to the location of the particle at time \( t \), and \( D \) is the diffusion coefficient. The standard deviation for \( x^2 \) is:

\[ \sigma(x^2) = 2Dt \]

In spherical coordinates, where \( r \) is the radial distance \( (r^2 = x^2 + y^2 + z^2) \),

\[ \sigma(r^2) = 6Dt \]

The diffusion coefficient is a parameter that can be calculated from the kinetic theory of gases in terms of the mean free path \( \lambda \) of the electrons or ions in the gas:

\[ D = \frac{1}{3} v \lambda \]  

(2-22)

Classically, the mean free path of electrons is four times longer than that of ions. For an ideal gas the mean free path is related to the temperature \( T \) and the pressure \( p \) in the following way:

\[ \lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma_0 p} \]  

(2-23)
where $\sigma_0$ is the total cross section for a collision with a gas molecule. Therefore, the expression for the diffusion coefficient in terms of the parameters of the gas is

$$D = \frac{2}{3\sqrt{\pi}} \frac{1}{p\sigma_0} \sqrt{\frac{(kT)^3}{m}} \quad (2-24)$$

Drift occurs in the presence of an electric field, when ions and electrons released from the ionizations generated by incoming radiation are accelerated along the electric field lines towards the anode and cathode. The average velocity is known as the drift velocity of each charge [51]. Drift velocities for ions are a lot slower than thermal velocities, but electrons can have pretty fast drift velocities because of their low mass.

The mobility of a charge can be defined as [51]

$$\mu = \frac{u}{E} \quad (2-25)$$

where $u$ is the drift velocity and $E$ the intensity of the electric field. For positive ions, the drift velocity depends linearly on the ratio between $E$ and $p$, so $\mu$ is constant at constant pressure. For ideal gases, the movement of charges is always at thermal equilibrium. The mobility is related to the diffusion coefficient in the following way [51]:

$$\frac{D}{\mu} = \frac{kT}{e} \quad (2-26)$$

This equation shows that the lower the temperature, the lower the electric field needs to be in order for the ions and electrons to move towards the electrodes.

Table 2-1 gives the mobility in cm$^2$V$^{-1}$s$^{-1}$ for certain ions in gases commonly used for proportional chambers.

In a mixture of $n$ gases $G_1, G_2, ..., G_n$, the mobility $\mu_i$ of an ion $C_i^+$ is given by the relation:

$$\frac{1}{\mu_i} = \sum_{j=1}^{n} \frac{P_{ij}}{\mu_{ij}} \quad (2-27)$$

where $P_{ij}$ is the concentration of gas $G_j$ in the mixture, and $\mu_{ij}$ is the mobility of ion $C_i^+$ in gas $G_j$ [31]. In a gas mix, the process of charge transfer takes place, and all ions
move rapidly around, except for a few with very low ionization potentials.

### 2.5.3. Charge multiplication

Charge multiplication in gaseous detectors occurs when the electrons resulting from primary ionizations gain enough energy (thanks to being accelerated by the electric field) to ionize molecules themselves. This generates secondary electrons, which will too gain enough energy to ionize molecules creating an avalanche of electrons, therefore exponentially multiplying the charge. The resultant positive ions drift slowly towards the cathode, while the electrons move quickly towards the anode, piling up and making the avalanche look like a drop of water (see Fig 2-12). This is called the Townsend avalanche.

\( \alpha \), known as the first Townsend coefficient, is the mean free path of electrons in a secondary ionization collision, so \( 1/\alpha \) is the probability of there being one ionization per unit of trajectory. If there are \( n \) electrons in a length \( dx \), there there will be \( dn \) new electrons from ionizations, where

\[
    dn = n\alpha dx
\]  

(2-28)

After integrating, the total number of electrons is

\[
    n = n_0e^{\alpha x}
\]  

(2-29)
2.5 Gaseous ionizing detectors

Figure 2-12: Formation of the avalanche. The electrons move faster than the positive ions, giving the avalanche the shape of a drop [24].

where $n_0$ is the initial number of electrons and $x$ is the length of the path of ionization, starting from the location of the primary ionization [24]. Then the multiplication factor is

$$M = \frac{n}{n_0} = e^{\alpha x} \tag{2-30}$$

where $M < 10^8$. This is known as the Raether limit, believed to be due to the effect of the space charge on the electric field.

The multiplication factor, also called gain, is very important in proportional counters, since their multiplication is proportional to the energy of incident particles. This is why $\alpha$ has been calculated for a number of different gases [49].

If the voltage applied between the electrodes is high enough, the primary electrons will be able to produce avalanches along their trajectory. The total ionization produced will depend on the length of the trajectory and the location of the primary ionization. For two events of the same energy, the position of the primary ionization affects the amplitude of the signal, making it difficult to relate amplitude with incident energy [33].

Depending on the type of detector, charge avalanches can occur in different places.
In a proportional counter, the avalanche will only occur close to the anode. In Geiger-Müller detectors, the electric field is so intense that avalanches can be produced anywhere in the gas \[61\]. And in triple GEM detectors, avalanches occur when the electrons enter the high-density electric field inside the holes of each GEM foil (see Section \[2.6\]).

### 2.5.4. Characteristic response curve

![Variation of ion pair charge with applied voltage](image)

**Figure 2-13**: Gaseous ionization detection regions - characteristic response curve

As can be seen in Figure \[2-13\], the total charge collected in a detector is a function of the voltage applied to it, which means the observed signal depends on the intensity of the electric field. While increasing the voltage in a gaseous detector, certain proportionality regions are obtained, which are represented on the graph by Roman Numerals I-VI:

- **I - Recombination Region**: The voltage is so low that the velocities reached by ions and electrons are very small, making it highly likely for them to recombine before they are collected. Information on detected particles can be lost so this region is not used for any type of detector.
2.5 Gaseous ionizing detectors

- **II - Ionization Chamber Region:** For low voltages, an ionization chamber collects the primary charge produced in the detector’s active volume. The amount of charge collected does not change as the voltage is increased. There is no recombination nor secondary ionizations, so it is ideal for medical dosimetry [31]. The gain is around 1, which means there is no multiplication. The amount of charge collected can be so low that an amplifier is needed in order to detect the signal.

- **III - Proportional Counter Region:** From a critical voltage onward, multiplication takes place. The detected signal is proportional to the energy deposited by incoming particles. This region is also called “ionization avalanche”. The formation of avalanches is produced rapidly, at a speed that depends on the drift time of the primary electrons from the time they are ejected from an atom to when they reach the anode. To maintain proportionality, it is important to use a quencher gas to control the avalanche (see Chapter 2.5.5). In this region, the gain can be between $10^3$ and $10^7$. The types of devices that work in this region are generally used in medical procedures such as X-rays and tomographies [12].

- **IV - Limited Proportionality Region:** The avalanche is too big, giving rise to great photoionizations [24]. The proportionality is lost due to the distortions of the electric field because of the accumulated charge close to the anode. Using a pulsed high voltage power supply may help reduce the amount of discharges. This region is usually not used in any type of detector. The gain is around $10^9$.

- **V - Geiger-Müller Region:** In this region, the avalanche extends to the whole anode. The photoionization is massive. The secondary ionizations and multiplications are so frequent that there is a real charge avalanche in each pulse. The pulses are big because of the large amount of collected charge, but the proportionality with the primary ionizations’ energy is lost. The counters, or Geiger-Müller detectors, that work in this region can only tell when there is radiation, but can’t be used to measure its energy. Yet, they are the most common type of detector due to how easy they are to operate, how quick they can be made, and how they are sturdy and can be moved around.

- **VI - Continuous Discharge Region:** At very high voltages there is a continuous
discharge, which is not useful for any counting or detecting. This discharge can sometimes be avoided by using a thick wire or special gas mixtures.

2.5.5. Choice of gas

In a gaseous ionizing detector any gas can be used, including air. Each gas has a different ionization energy, or minimum energy required for its atoms to be ionized. Table 2-2 lists the ionization and excitation energies of the most common gases, along with the mean energy for the creation of an electron-ion pair.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Excitation energy (eV)</th>
<th>Ionization energy (eV)</th>
<th>Mean electron-ion energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>10.8</td>
<td>15.4</td>
<td>37</td>
</tr>
<tr>
<td>He</td>
<td>19.8</td>
<td>24.6</td>
<td>41</td>
</tr>
<tr>
<td>N₂</td>
<td>8.1</td>
<td>15.5</td>
<td>35</td>
</tr>
<tr>
<td>O₂</td>
<td>7.9</td>
<td>12.2</td>
<td>31</td>
</tr>
<tr>
<td>Ne</td>
<td>16.6</td>
<td>21.6</td>
<td>36</td>
</tr>
<tr>
<td>Ar</td>
<td>11.6</td>
<td>15.8</td>
<td>26</td>
</tr>
<tr>
<td>Kr</td>
<td>10.0</td>
<td>14.0</td>
<td>24</td>
</tr>
<tr>
<td>Xe</td>
<td>8.4</td>
<td>12.1</td>
<td>22</td>
</tr>
<tr>
<td>CO₂</td>
<td>10.0</td>
<td>13.4</td>
<td>33</td>
</tr>
<tr>
<td>CH₄</td>
<td></td>
<td>13.1</td>
<td>28</td>
</tr>
<tr>
<td>C₄H₁₀</td>
<td></td>
<td>10.8</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 2-2: Characteristic energies for common gases [49]

Generally, a gas to fill a gaseous detector needs to satisfy multiple requirements, including being ionized at the lowest possible voltages, allowing a high gain, having good proportionality, high rate capacity, long half-life, and permitting high mobility. These conditions are better satisfied with a mix of gases than with just one. To be ionized with a low voltage, the best options are gases that are inert and need the lowest electric fields in order to form avalanches, such as noble gases [24]. This happens because noble gases can only be excited through the absorption and emission of photons [61]. Out of these, argon is
the most commonly used due to its relatively low ionization energy of 15.76eV (compared to other noble gases), low cost, availability, and safety (hydrogen is flammable, and helium is expensive and scarce).

However, due to its low ionization energy, using pure argon as a gas only allows gains of up to $10^3$ to $10^4$ before discharges and sparks start occurring. Mixing it with a second, polyatomic, gas can help fix this problem. Some examples that work well are methane, alcohol, CO$_2$, and BF$_3$. Since they have a large amount of non-radiative excited states (such as vibrational and rotational), these molecules act as inhibitors by absorbing photons of all energies being radiated by the de-excitations of the noble gas atoms [61]. They then dissipate this extra energy through simple radical dissociations or elastic collisions. For this reason, these gases are called “quenchers”. Even a small percentage of quencher in the gas mix may increase the gain up to $10^6$. For GEM detectors, the most common gas mixture is between 10 – 30 % carbon dioxide and between 70 – 90 % argon.

2.5.6. Limitations

Gaseous detectors present some limitations in their performance. These limitations are mainly caused by [29]:

- Dissociation of the detector gas and possible formation of polluting substances
- Formation of highly reactive radicals
- Polymerization of the quencher
- Deposition of insulators in the anodes and cathodes, which increases the diameter of the anode, therefore reducing and varying the electric field and modifying the gain and energy resolution

2.6. The Triple-GEM detector

GEM detectors consist of an anode, a cathode, and a GEM foil in between (see Fig. 2-14). A GEM foil is a 50 $\mu$m thick insulating kapton layer covered with copper on both sides, and a grid of 50 - 100 holes per square millimeter perforated using laser techniques.
The holes have a diameter of 70 µm, a separation of 140 µm, and a double-conical shape (Figure 2-15). The anode is covered in a two-dimensional strip readout of 256x256 detection areas that connects to the electronics, which allows for precise measurements of the location of an incoming particle. These strips are made of copper, so electrons induce a charge in them. This is all placed inside a tight box and filled with gas. The most common gas mixture is argon and carbon dioxide at a ratio of 70 to 30. Argon is used because it is a noble gas, easily ionizable (its ionization energy is only 15.76eV), cheap, and easy to get. Hydrogen is not used because it is flammable and reactive, while helium is expensive and scarce. Carbon dioxide, being organic, is used as a quencher because it absorbs the photons that are produced during ionizations and that would otherwise hurt the image resolution. These organic gases are perfect for this job because their absorption spectrum lies at exactly the energy of the released photons. The quencher gas also lowers the chance of sparks when the voltage is increased.

![Figure 2-14: Schematic view of a single-GEM detector](image)

Using a high voltage (HV) source, a potential difference is achieved between the anode and the cathode, generating an electric field between the electrodes. Since kapton is an insulator and copper is a conductor, the electric field lines will bend inside the holes of the GEM foil so as to avoid the kapton, and other lines will go from the positive copper electrode to the negative one, as in Figure 2-16. In these lines, 40% of free electrons will get caught and will have to be recovered using the energy trigger, since they will never reach the strip readout. The energy trigger is a fast trigger readout at the bottom copper electrode of the third GEM foil. It doesn’t give information about the path or location of
2.6 The Triple-GEM detector

![Image of GEM foil]

Figure 2-15: Electron microscope view of a GEM foil. The hole diameter and pitch are 70 and 140 $\mu$m, respectively [70].

The incident particle because it doesn’t have a readout grid, but it can detect a signal so that total multiplication can be determined. If the HV voltage used is not enough to guide the electrons to the holes of the GEM foils quickly enough, many will join the positive ions that were left after the gas was ionized in a process called *recombination*. These electrons will never be recollected at the readout pane and the signal will therefore be lost.

![Image of electric field]

Figure 2-16: The electric field in the region of the holes of a GEM electrode [62]

As is the case with most ionizing gaseous detectors, when ionizing radiation such as photons or muons enters a GEM detector, it interacts with the particles of the gas mixture inside it, ionizing the argon atoms. Free electrons are created and drift towards the GEM foil following the electric field lines. They are guided inside the holes where, because of the increased density of field lines, the force is stronger and gives them a large velocity.
After leaving the holes, each of these electrons now has enough energy to ionize particles of the gas, creating even more electrons. Since this is repeated for most of the electrons generated by the incident photons, multiplication takes place. After this process happens, the electrons continue their trajectory onto the readout pane where a signal is detected.

With a single GEM foil, the gain is approximately 100 or 200 at about 400 V. However, GEM foils can be piled up on top of each other, forming double, triple, or even higher-level GEMs. Each gain is multiplied so, taking losses into account, a triple-GEM like the one owned by Universidad Nacional de Colombia could provide a gain of $10^4$ or $10^6$ using relatively low voltages. Since low voltages are used, the chance of getting sparks and therefore damaging the detector is greatly reduced. For this reason, GEM-based detectors are a safe, durable, and effective option for detecting ionizing radiation.

**Figure 2-17:** Drift, multiplication, and collection of charges in a triple-GEM detector. The amplifier is a charge pre-amplifier.

Additionally, since the triple-GEM detector falls into the gaseous ionizing detectors category, it should replicate the Characteristic Response Curve when the collected charge is plotted in a logarithmic scale against applied voltage (see Chapter 2.5.4). Therefore, aiming to replicate this curve is an effective way of determining the correct functioning of
2.7 Dosimetry

2.7.1 Definition of dosimetric quantities

- Absorbed dose

Absorbed dose is the sum of the energy deposited in a medium by ionizing radiation, which is partly determined by its intensity. The absorbed dose in a medium $D_{med}$ is related to the energy fluence $\psi$ through

$$D_{med} = \frac{dE}{dm} = \psi \left( \frac{\bar{S}_{col}}{\rho} \right)_{med}$$

(2-31)

according to Bragg-Gray Cavity Theory (see Section 2.7.3), where $dE$ is the energy absorbed by a volume of mass $dm$.

For a primary photon beam, the fluence of electrons is given by all secondary electrons generated by it. When transient charged particle equilibrium (TCPE) exists, the dose can be expressed as [9]:

$$D^{TCPE} = K_{col} \ e^{\mu' \bar{x}}$$

(2-32)

where $\mu'$ is the common slope of $D$ and $K_{col}$ and $\bar{x}$ is the range of the secondary electrons [77].

In order to determine the absorbed dose in a medium, any direct or indirect effect of ionizing radiation can be used. These can include the ionizing of a gas or a solid, the emission of light, the blackening of a photographic film, or a chemical change [77].

The interaction of radiation with gas molecules inside a detector generates ion pairs, which can be measured as a current in a picoammeter. In clinical dosimetry there are two different designs of ionization chambers: parallel and cylindrical. A parallel plane chamber has two electrodes that are parallel to each other and perpendicular to the direction of the beam. The gas between these electrodes is the sensitive volume of the
detector. This chamber is usually used for dosimetry with energetic electrons. With photons, the most used ionization chambers for dosimetry are cylindrical, known as thimble or compact chambers. The electrode is in the center and the cylindrical cavity surrounding it is filled with gas [77].

![Figure 2-18](image)

**Figure 2-18:** Geometries of cylindrical (left) and parallel plane (right) ionization chambers. The radiation is coming from the top [8].

- **Mass attenuation coefficient**

  When a beam of monoenergetic photons penetrates through a length $x$ of a material of density $\rho$, its original intensity $I_0$ is attenuated according to the exponential attenuation law:

  $$ I = I_0 e^{-\frac{\mu}{\rho}x} $$  \hspace{1cm} (2-33)

  $\mu/\rho$ is called the mass linear attenuation coefficient of the material. This equation can be rewritten as:

  $$ \frac{\mu}{\rho} = \frac{\ln \left( \frac{I_0}{I} \right)}{x} $$  \hspace{1cm} (2-34)

  Therefore, the mass attenuation coefficient can be calculated experimentally from the intensities of the beam and the thickness of the absorbing material. The theoretical value of $\mu/\rho$ is defined in terms of the total atomic cross section $\sigma$ and the atomic weight $w$ as follows:
Table 2-3: Mass attenuation coefficients for photons in argon gas of the typical energies used in radiology [56]

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>$\mu/\rho$ (cm$^2$/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>8.629</td>
</tr>
<tr>
<td>30</td>
<td>2.697</td>
</tr>
<tr>
<td>40</td>
<td>1.228</td>
</tr>
<tr>
<td>50</td>
<td>0.7012</td>
</tr>
<tr>
<td>60</td>
<td>0.4664</td>
</tr>
<tr>
<td>80</td>
<td>0.2760</td>
</tr>
<tr>
<td>100</td>
<td>0.2043</td>
</tr>
<tr>
<td>150</td>
<td>0.1427</td>
</tr>
</tbody>
</table>

\[
\frac{\mu}{\rho} = \sigma \frac{N_A}{w} \tag{2-35}
\]

where $N_A$ is Avogadro’s number. Generally though, the mass linear attenuation coefficient for a common material used in detector physics is looked up in standardized tables from official sources, such as the National Institute of Standards and Technology (NIST) or the ICRU documents.
Kerma

Photons can be considered as indirectly ionizing radiation that transfers an energy $dE_{tr}$ to secondary charged particles, which in turn release their energy in a medium of mass $dm$. “Kinetic energy released per unit mass”, or kerma, is a quantity that describes conceptually the idea of liberating kinetic energy [9]. Its definition can be expressed in terms of the photon fluence $\Phi$ and the mass-energy transfer coefficient $\mu_{tr}/\rho$ [70]:

$$K = \frac{dE_{tr}}{dm} = \Phi E \frac{\mu_{tr}}{\rho}$$

Kerma is given in J/kg or grays Gy. For a polyenergetic photon spectrum, kerma is the integral of the fluences and their energy transfer coefficients.

Using the definition of energy fluence $\psi = \Phi E$ and describing only the fraction of the kerma resulting from collisions of secondary electrons,

$$K_{col} = \psi \frac{\mu_{en}}{\rho} = \psi \frac{\mu_{tr}}{\rho} (1 - \bar{g})$$  \hspace{1cm} (2-37)
where $\mu_{en}$ is the energy absorption coefficient and $\bar{g}$ is the radiative fraction of local energy depositions corrected for energy-losses due to Bremsstrahlung \[77\].

- Charged-Particle Equilibrium

Charged-Particle Equilibrium, or CPE, exists in a closed volume when the number of charged particles and the total energy leaving the volume is equal to the number of charged particles and the total energy entering the volume. For a primary photon beam, CPE occurs at depths greater than the maximum range of secondary electrons generated by it \[77\]. In real life true CPE is never reached due to the attenuation of photons, but a transient CPE (TCPE) can be defined as $\beta = D/K_{col} > 1$. In the hypothetical situation where CPE exists and no photon attenuation occurs, $\beta = 1$.

- Linear Energy Transfer

The linear energy transfer (LET) is the amount of energy that the incoming particle transfers to the medium per unit distance. The LET is closely related to the stopping power in that the unrestricted LET is the same as the linear electronic stopping power. However, the total stopping power includes the nuclear stopping power, and because it doesn’t cause electronic excitations, it is not included in the LET.

Delta rays, the secondary electrons produced during ionizations by primary charged particles, have enough energy to ionize more atoms of the medium. Sometimes only the energy transferred in the vicinity of the primary particle’s track is counted, excluding interactions that produce delta rays with energies larger than a certain value $\Delta$. This energy limit does not take into account secondary electrons that carry energy far from the primary particle track, since a larger energy implies a larger range \[44\]. This energy transferred per unit distance is what is called restricted LET:

$$L_{\Delta} = \frac{dE_{\Delta}}{dx}$$  \hspace{1cm} (2-38)

where $dE_{\Delta}$ is the energy lost by the charged particle due to electronic collisions in a distance $dx$, excluding secondary electrons with kinetic energy larger than $\Delta$. If $\Delta$ tends toward infinity, all electrons have $E_k < \Delta$, and the LET becomes the unrestricted LET which is identical to the linear electronic stopping power.
2.7.2. Absolute and relative dosimetry

Estimating a dose to a patient is not a simple process. First, ionization chambers calibrated in primary laboratories are used to measure doses in hospitals. The procedures for reference dosimetry are specified in national and international dosimetry protocols and codes of practice. The estimation of individual doses to patients during treatments are based on different models and planning systems. These are connected to the measured dose value under reference conditions.

The general concept of clinical dosimetry in the context of radiotherapy is shown in Figure 2-19. There are two types of dose measurement: absolute dosimetry (also called reference dosimetry), and relative dosimetry. The image shows what has to be done in order to determine the dose received by a patient once the dose to the medium has been measured at reference or non-reference conditions.

![Conceptual map of clinical dosimetry in radiation therapy](image)

**Figure 2-19**: Conceptual map of clinical dosimetry in radiation therapy [77]

In clinics, the user works with ionization chambers calibrated at a Secondary Standard Dosimetry Laboratory (SSDL), which is usually the manufacturer itself. The corresponding calibration coefficient $N_{D,w}$ of each chamber has to be traceable to a Primary Standard Dosimetry Laboratory. This is almost always a national institution that is at least in part involved in defining the national dosimetry protocols [77]. If the user’s beam quality is different from the beam quality used in calibration, a correction factor $k_Q$ is provided by these protocols. For low energy photons, the beam quality is defined by their half-value
layer (HVL), for high energy photons by their tissue-phantom ratio (TPR<sub>20,10</sub>), and for electrons by the depth at which the dose is 50% of the maximum (R<sub>50</sub>).

Relative dosimetry is used both for quality control measurements and to characterize radiation machines [77]. Both absolute and relative dosimetrizations are used to calculate the dose to the patient, either by analytical methods or through Monte-Carlo simulations.

2.7.3. Cavity Theory of dosimetry

A cavity is described as a sensitive medium of a dosimeter or detector with a defined volume V filled with gas and separated from an outer medium by a wall. The dose absorbed by a detector’s cavity \( D_{\text{det}} \) is given by [70]:

\[
D_{\text{det}} = \frac{dE}{dm} = \frac{Q_{\text{prim}}}{\rho V} \frac{W_{\text{gas}}}{e}
\]

(2-39)

where \( Q_{\text{prim}} \) is the total charge of the ions of a single sign created inside the cavity due to the incoming radiation, \( \rho \) is the density of the gas, \( V \) the volume of the cavity, \( W_{\text{gas}} \) the energy needed to create an ion pair in the gas, and \( e \) the electron’s charge. \( D_{\text{det}} \) is given in grays Gy if \( Q \) is expressed in coulombs C, \( m \) (the mass of the gas) in kg and \( W_{\text{gas}}/e \) (the mean energy spent per unit charge produced) in joules per coulomb J/C.

If proportionality exists, a factor \( f \) can be used to find the dose in the medium from the dose measured by the detector. More explicitly:

\[
D_{\text{med}} = f \cdot D_{\text{det}}
\]

(2-40)

Cavity theory is used to determine the factor \( f \). This theoretical relation was developed by Bragg and Gray in the 1950’s [77]. Now, there are a number of theories that describe absorbed dose in cavities, such as Bragg-Gray Theory, Spencer-Attix Theory, and Theory for Big Cavities [7]. The first two are for small cavities with respect to the range of the incident particles. The different theories explain how to go from the absorbed dose in the detector to absorbed dose in the medium.

Bragg-Gray Theory

Several conditions need to be met for Bragg-Gray Theory to be valid. The first is that the cavity must be small compared to the ranges of secondary electrons such that its
presence doesn’t modify the fluence of charged particles (the number of electrons crossing
the cavity and their energies are basically the same as those in the ‘undisturbed’ medium).
This condition is also satisfied when the material of the cavity is of very similar atomic
composition to the medium. For the photon energies used in radiotherapy, only cavities
filled with gas fulfill this requirement [7]. Additionally, the absorbed dose in the cavity
must be deposited only by electrons that completely cross the cavity, so it doesn’t include
that of electrons formed inside the cavity (secondary electrons) or electrons that stop
inside the cavity. This means that the dose resulting from photon interactions in the cavity
must be negligible [7]. Therefore, when charged-particle equilibrium (CPE) exists in the
medium, inserting a Bragg-Gray cavity should not perturb the ‘equilibrium spectrum’ of
charged particles [23]. Detectors usually fulfill the Bragg-Gray conditions with megavoltage
radiation but not with kilovoltage X-rays.

The dose absorbed in the medium is given by a different equation depending on the
type of particle. They are given in terms of the electronic (collision) kerma $K_{col}$, the particle
fluence of the medium $\Phi_{med}$ (defined as $\Phi = dN/dA =$ number of incident particles over
cross sectional area in m$^{-2}$), the particle fluence differential in energy $\Phi_E = d\Phi/dE$ (also
known as the primary electron fluence spectrum), the energy fluence of the medium $\psi = E \cdot \Phi_{med}$, the energy fluence differential in energy $\psi_E = d\psi/dE$, the mass energy-absorption
coefficient for the medium $[\mu_{en}/\rho]_{med}$, and the mass electronic stopping power averaged over
the whole spectrum $[\bar{S}_{el}(E)/\rho]_{med}$. At CPE conditions, they are:

- Monoenergetic photons:
  \[ D_{med} = K_{col} = \psi \cdot [\mu_{en}/\rho]_{med} \]

- Polienergetic photons:
  \[ D_{med} = K_{col} = \int_0^{E_{max}} \psi_E(E) \left[ \mu_{en}(E)/\rho \right]_{med} dE \]

- Monoenergetic charged particles:
  \[ D_{med} = \Phi_{med} \cdot [\bar{S}_{el}/\rho]_{med} \]

- Polienergetic charged particles:
  \[ D_{med} = \int_0^{E_{max}} \Phi_{E,med} \left[ \bar{S}_{el}(E)/\rho \right]_{med} dE \]
For example, when the previous conditions are met and using $D_{\text{med}} = \Phi_{\text{det}}(\bar{S}_{\text{el}}/\rho)_{\text{med}}$ for a monoenergetic charged particle, the ratio between doses is:

$$f = \frac{D_{\text{med}}}{D_{\text{det}}} = \frac{\Phi_{\text{med}}(\bar{S}_{\text{el}}/\rho)_{\text{med}}}{\Phi_{\text{det}}(\bar{S}_{\text{el}}/\rho)_{\text{det}}} = (\bar{S}_{\text{el}}/\rho)_{\text{med,det}}$$

(2-41)

because $\Phi_{\text{med}} = \Phi_{\text{det}}$.

The expression for the dose ratio for polienergetic charged particles is:

$$f = \frac{\int_0^{E_{\text{max}}} \Phi_{E,\text{med}}^{\text{prim}} [\bar{S}_{\text{el}}(E)/\rho]_{\text{med}} dE}{\int_0^{E_{\text{max}}} \Phi_{E,det}^{\text{prim}} [\bar{S}_{\text{el}}(E)/\rho]_{\text{det}} dE}$$

(2-42)

where $\Phi_{E}^{\text{prim}} = NR_{CSDA}$ is the primary electron fluence spectrum. This quantity is now obtained by Monte Carlo simulation, but previously analytical methods were used.

Consider a small cavity filled with a certain material and surrounded by a homogeneous medium given by a radioactive source emitting $N$ identical charged particles per unit mass isotropically, each with kinetic energy $E_0$. At CPE:

$$D_{\text{med}} = K_{\text{med}} = NE_0$$

(2-43)

so

$$\Phi^{\text{prim}} = \int_0^{E_0} \Phi_{E}^{\text{prim}} dE = \int_0^{E_0} \frac{N dE}{[S_{\text{tot}}(E)/\rho]_{\text{med}}} = NR_{CSDA}$$

(2-44)

$\Phi_{E,\text{med}}^{\text{tot}}$ and $\Phi_{E,det}^{\text{tot}}$ “can only be obtained from a detailed Monte Carlo simulation of the complete situation, with and without the detector” [7].

**Spencer-Attix Theory**

The conditions that need to be met for Spencer-Attix Theory to be valid are that the cut-off energy $\Delta$ is defined according to the size of the cavity; all the incident electrons have an energy greater than $\Delta$, electrons for which the energy loss is less than $\Delta$ are treated as locals (which means they stay inside the cavity or the medium where they were created), and $\Delta$ must be just enough for the particles to cross the cavity [7]. For radiotherapy, $\Delta \sim 10 - 15$keV.

The Spencer-Attix theory includes an additional term that takes into account the secondary $\delta$-electrons produced inside of the cavity, since it understands that some secondary
electrons may have enough energy to leave the cavity and reduce the absorbed dose in the detector. Therefore, it uses the restricted stopping power LET \( L \) with a maximum energy limit of \( \Delta \). This divides the dose into two separate terms:

1. \( D_{1,\text{det}} \) for secondary electrons of \( E_k < \Delta \): slow electrons that deposit their energy \( E_k \) inside the cavity

2. \( D_{2,\text{det}} \) for secondary electrons of \( E_k > \Delta \): fast electrons that leave the cavity before losing all their energy

Using the definition \( L_\Delta = \frac{dE_\Delta}{dl} \), where \( l \) is the average length that a particle travels inside a Spencer-Attix cavity (also called \( R_{\text{CSDA}} \)), these two terms can be expressed as:

\[
D_{1,\text{det}} = \int_{\Delta}^{E_k} \Phi_{E_k}^\delta(E_k) \frac{L_{\Delta,\text{det}}(E_k)}{\rho} dE_k \tag{2-45}
\]

\[
D_{2,\text{det}} = \Phi_{E_k}^\delta(\Delta) \frac{S_{\text{det}}(\Delta)}{\rho} \Delta \tag{2-46}
\]

This means that the total absorbed dose in the detector is given by:

\[
D_{\text{det}} = \int_{\Delta}^{E_k} \Phi_{E_k,\text{det}}^\delta(E_k) \frac{L_{\Delta,\text{det}}(E_k)}{\rho} dE_k + \Phi_{E_k,\text{det}}^\delta(\Delta) \frac{S_{\text{det}}(\Delta)}{\rho} \Delta \tag{2-47}
\]

The ratio of absorbed dose in the medium to absorbed dose in the detector is then given by [7]:

\[
\frac{D_{\text{med}}}{D_{\text{det}}} = \frac{\int_{\Delta}^{E_k} \Phi_{E_k,\text{med}}^\delta(E_k) \frac{L_{\Delta,\text{med}}(E_k)}{\rho} dE_k + \Phi_{E_k,\text{med}}^\delta(\Delta) \frac{S_{\text{med}}(\Delta)}{\rho} \Delta}{\int_{\Delta}^{E_k} \Phi_{E_k,\text{det}}^\delta(E_k) \frac{L_{\Delta,\text{det}}(E_k)}{\rho} dE_k + \Phi_{E_k,\text{det}}^\delta(\Delta) \frac{S_{\text{det}}(\Delta)}{\rho} \Delta} \tag{2-48}
\]

Dosimetry expert Pedro Andreo did a Monte-Carlo simulation and obtained the following formula for the average length that particles travel inside a chamber that behaves as a Spencer-Attix cavity [7]:

\[
l = \frac{4V}{a} \tag{2-49}
\]

where \( V \) is the cavity’s volume and \( a \) is its superficial area.

The relationship between this range \( l \) and the cut-off energy \( \Delta \) can be found approximately in the graph of Figure 2-20.
Figure 2-20: Relationship between the average length that particles travel inside a chamber and the cut-off energy

Since the stopping powers need to be calculated at the cut-off energy to be able to use the Spencer-Attix formulas, it can be difficult to know which energy to use for polienergetic cases. To calculate the stopping power of a polienergetic beam, the graph of Figure 2-21 can be used. It was obtained by Andreo from Monte-Carlo simulations, and shows the relationship between the stopping powers of monoenergetic and polienergetic beams. In this graph, $y$ is the cut-off energy for the polienergetic beam, $\bar{k}$ is the monoenergetic equivalent to this energy, $E_e$ is the energy of primary electrons, and $E_z \approx E_e/2$ is the average energy of the spectrum ($E_z$ is the energy used to calculate the stopping power of the polienergetic beam from the tables).

The average primary energy for secondary electrons generated by high energy collisions of monoenergetic photons interacting via Compton scattering is given by:

$$\bar{E}_e = \bar{k} \frac{e^\sigma_{C,KN}^{tr}}{e^\sigma_{C,KN}}$$

(2-50)

where $e^\sigma_{C,KN}$ is the Klein-Nishina cross section for Compton Scattering. Converting values using the graph, this equation can also be used for polienergetic photons.
Figure 2-21: Relationship between the stopping powers of monoenergetic and polienergetic beams. $y$ is the cut-off energy for the polienergetic beam, $\bar{k}$ is the monoenergetic equivalent to this energy, $E_e$ is the energy of primary electrons, and $E_z \simeq E_e/2$ is the average energy of the spectrum ($E_z$ is the energy used to calculate the stopping power of the polienergetic beam from the tables).

Big cavity theory

A large cavity is a cavity big enough so that the dose from electrons created by photon interactions inside it is much larger than the dose from secondary electrons originating outside the cavity [60]. The ratio between dose absorbed in the medium and dose absorbed in the detector for particles of energies lower than 1 MeV is:

$$\frac{D_{med}}{D_{det}} = \frac{K_{col,med}}{K_{col,det}} = \frac{\left(\bar{\mu}_{en}/\rho\right)_{med}}{\left(\bar{\mu}_{en}/\rho\right)_{det}}$$  (2-51)
Ionization chamber

For an ionization chamber with a high energy particle beam, and taking into account all correction factors (small perturbations), the dose absorbed in the medium is:

\[ D_{\text{med}} = \frac{Q}{m} \left( \frac{W_{\text{gas}}}{e} \right) \frac{S_{\text{med}}}{S_{\text{gas}}} P_{f1} P_{\text{dis}} P_{\text{wall}} P_{\text{cel}} \]  \hspace{1cm} (2-52)

where the stopping powers are the Spencer-Attix ones, \( W_{\text{gas}} \) is the average energy expended in air per ion pair formed, \( P_{f1} \) is the electron fluence perturbation correction factor, \( P_{\text{dis}} \) is the correction factor for displacement of the effective measurement point, \( P_{\text{wall}} \) is the wall correction factor, and \( P_{\text{cel}} \) is the correction factor for the central electrode \[60\].

If an ionization chamber is calibrated in terms of absorbed dose in water and used at reference conditions, no cavity theory is needed. Instead,

\[ D_{\text{med}} = M_{\text{det}} N_{\text{med},Q} \]  \hspace{1cm} (2-53)

where \( M_{\text{det}} \) is the measurement obtained from the detector and \( N_{\text{med},Q} \) is the calibration coefficient for a beam of quality \( Q \).

When the mean atomic number \( Z \) of the cavity material and the medium are similar (such as air and water or graphite), there is not much difference between the Spencer-Attix and Bragg-Gray formulations of the dose ratios. Around 20\% of the energy transferred to air-cavity-generated \( \delta \) rays will ‘escape’ the cavity, so if this 20\% is balanced by the energy of incoming \( \delta \) rays, the dose ratios for Spencer-Attix and Bragg-Gray are precisely equal.

None of these theories necessarily has to be used, though. It may be easier to determine the dose ratio experimentally or by Monte Carlo simulation \[66\]. With this approach, no explicit cavity theory is required; there is no need to separate the dose ratio into the product of a stopping-power ratio and several perturbation factors \[7\].

2.7.4. Triple-GEM detector as a dosimeter

For a detector to be useful for dosimetry it must have high precision (reproducibility), accuracy, dose sensitivity, small directional dependence, a linearity of signal with dose over
a wide range of energies, it should preferably be independent of dose rate, have a maximum
dose above the expected dose range to be measured, good spatial resolution, large dynamic
range, and ease of handling in a clinical environment [23].

Since the GEM detector has a 2D sensor with a micrometer-sized resolution it does
have high accuracy and spatial resolution. The precision comes from taking measurements
in reference conditions. The energy range at which it is a linear detector is large, because
of its big dynamic range. And the directional dependence is almost non-existent because
any particle that can come into the detector can ionize the gas particles, regardless of its
incident direction.

Additionally, GEM detectors are proportional counters (the signal is proportional to
the number of incident charges; the amplified induced signal is registered as one count).
Therefore, the GEM detector is expected to be useful for determining radiation dose. In
theory, every time an individual photon interacts with the gas in the detector, a count is
registered. If this were the case, the fluence could be measured and used to calculate the
dose directly. However, this scenario is unrealistic [23]. Yet, the approximate dose can be
calculated from the energy spectrum or from the ionization current.

Absorbed dose is defined as the expectation value of the energy deposited in a volume
of matter per unit mass (see Sec 2.7.1):

\[ D = \frac{dE_{\text{abs}}}{dm} \]  

(2-54)

It is measured in Joules per kilogram, or grays (Gy). This energy is what causes
ionizations along the path of a charged incident particle, but it can’t be measured directly
with the detector. What can be measured is current, which gives information about the
amount of charge generated. Then, using the Bragg-Gray cavity theory (see Sec 2.7.3),
these two values can be equated in the following way:

\[ D_{\text{gas}} = \frac{Q_{\text{prim}}}{m_{\text{gas}}} \frac{\bar{W}_{\text{gas}}}{e} \]  

(2-55)

where \( D_{\text{gas}} \) is the dose to the gas, \( Q_{\text{prim}} \) is the charge produced through gas ionizations,
\( m_{\text{gas}} \) is the mass of gas and \( \bar{W}_{\text{gas}}/e \) is the average energy required to cause one ionization
in that specific gas [15]. For argon, this value ranges around 26 eV per ion pair = 26 J/C,
while for CO\(_2\) it is 33 eV, as can be seen in table [2-5] [15] [21] [27].
Table 2-5: Energy per ionization and loss of energy per unit length for a minimum ionizing particle in Ar and CO$_2$

<table>
<thead>
<tr>
<th>Gas</th>
<th>$W$ (eV)</th>
<th>$dE/dx$ (keV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>26</td>
<td>2.44</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>33</td>
<td>3.01</td>
</tr>
</tbody>
</table>

To calculate the energy required to generate an electron-ion pair in a specific gas mix, such as Ar-CO$_2$ at a ratio of 75% − 25%, the following procedure is used:

$$
\frac{1}{W_{Ar-CO_2}} = \frac{\%Ar}{W_{Ar}} + \frac{\%CO_2}{W_{CO_2}} = \frac{0.75}{26eV} + \frac{0.25}{33eV} = \frac{1}{27.5eV}
$$

so $W_{Ar-CO_2} = 27.5$ eV \[78\].

The mass of gas can be determined from the density of the gas and the volume of the cavity. The density of argon is $1.652 \times 10^{-3}$ g/cm$^3$, and the density of carbon dioxide is $1.827 \times 10^{-3}$ g/cm$^3$ at 18°C. The volume of the cavity is given by the $10 \times 10 cm^2$ area, multiplied by a 3mm drift region, two 2mm transfer regions, and a 2mm induction region. This gives a total gas mass of $0.153 \times 10^{-3}$ kg.

When the incident dose is known for the specific gas used, it can be converted into dose in air to compare with the values given by other dosimeters. The lower limit of dose that can be measured with a detector is determined by the background. The background must be subtracted from the reading in order to get an accurate dose measurement. This background noise comes from both the detector (electronic noise) and the environment. Measurements only start becoming reliable when they are more than twice the size of the background noise. The higher limit of dose that can be measured with the detector depends on the detector’s limit using its least sensible range.

The triple-GEM detector can’t be considered a small cavity with respect to the ranges of secondary electrons produced. Because the dose contribution from secondary electrons originating outside the cavity can be ignored when compared to the contribution of electrons created by photon interactions within the cavity of a triple-GEM detector, Big Cavity Theory is the best cavity theory to approximate dose in the medium. Therefore, the ratio between dose absorbed in the medium and dose absorbed in the detector for particles of
energies lower than 1 MeV is:

$$\frac{D_{med}}{D_{det}} = \frac{K_{col,med}}{K_{col,det}} = \left( \frac{\bar{\mu}_{en}}{\rho} \right)_{med,det}$$

(2-57)

Yet, this is only an approximation. Doing experimental calibrations or Monte Carlo simulations is still a more exact method of converting dose from the detector to the medium.
3 Experimental setup and methodology

This project was developed at the CRYOMAG Particle Detectors Laboratory at Universidad Nacional de Colombia, where all of the necessary equipment, tools, instruments, and devices were readily available for this project.

3.1. Instruments and devices

The instruments used in this experiment were the triple-GEM detector, an electronics crate with several NIM (Nuclear Instrument Module) standard modules, an oscilloscope, a dual counter, a picoammeter, a Geiger-Müller radiation detector, a gas pipe, a flowmeter, and several radioactive sources. Their functions, brands, and models are explained in detail below.

- Triple-GEM detector: The detector owned by CRYOMAG research group was obtained from CERN in the frame of the RD51 Collaboration. It was assembled at CERN. It has all the properties that have been described throughout this document, and is the subject of this investigation. The triple-GEM detector includes a connection to a high voltage supply, a gas input regulated by a flowmeter, and signal outputs located at the strips and at the bottom of the third GEM foil (Figs. 3-1, 3-2). Any or both of these signal outputs are then sent to the required electronics that depend on the specific application. Depending on the signal output used to generate the pulses, the polarity is different; pulses taken from the strips output are negative and pulses taken from the bottom of the third GEM foil output are positive. Both signal outputs generate the same results, except for the polarity (see Section 4.1). Most results were obtained from the bottom of the third GEM foil output so they have positive polarity.
The Triple-GEM detector’s 512x512 strips would allow for a very high spatial resolution from the strips output with the right electronics. However, in Colombia the right electronics are impossible to import because of nuclear regulations. It was necessary to use simpler electronics to combine 256 channels into a LEMO connector, obtaining a single signal for each detection. This provides useful for 1D dosimetry but limits the possibility of having a good two-dimensional spatial resolution.

**Figure 3-1**: Voltage divider circuit, signal outputs, and geometrical diagram of the triple-GEM detector. The high voltage supply is connected at the top left corner, labeled “-HV”. The GEM3B output represents the signal output located at the bottom of the third GEM foil. The whole structure is placed inside a tight box with an input and an output of gas, such that there is a permanent flow of gas while the detector is operating.

- Operating gas tank: 7m³, filled with 75% argon and 25% carbon dioxide. It has its own pressure and opening valves with specialized manometers, regulated to an output pressure of 0.3 Kgf/cm². The manometer is connected through a 6mm tube to the flowmeter that leads to the detector’s gas entrance (Fig. 3-3).
Flowmeter: A Dwyer flowmeter is used to measure the flow of Ar+CO₂ through the detector. It has units of l/min and a maximum value of 0.5 l/min. It was calibrated...
with air (Fig. 3-4).

The gas is already mixed at 75% Argon and 25% CO$_2$ in the gas tank. As it leaves the tank, it reaches the flowmeter, where the user can adjust the flow using the knob. The gas leaves the flowmeter directly towards the triple-GEM detector, and enters through the gas input connector (see Fig. 3-2).

![Dwyer flowmeter](image)

**Figure 3-4: Dwyer flowmeter**

- Victoreen RAD-CHECK plus Model 06-526: open ionization chamber. This detector measures exposure in röntgen (R) and exposure rate in R/min. The radius of the detector's active area is 3.6cm. It was calibrated in Lima, Peru in 2017 using the substitution method with 70kVp X-rays, and gave a calibration factor of $N_K = 0.921$. Because it works with air, it also requires a $K_{TP}$ temperature and pressure correction factor. Every measurement taken with it needs to be multiplied by these two factors. Additionally, it was calibrated such that one röntgen R of exposure equals one centigray cGy of absorbed dose (Fig. 3-5).
Digital Radiation Monitor: Radiation Alert - Inspector EXP detector is a Geiger-Müller type detector. It measures radiation as exposure, in mR/hr or $\mu$Sv/hr, as particle fluence, in CPM or CPS, or as a timed count. Its operating ranges are from -0.001 to 100 mR/hr, from -0.01 to 1000 $\mu$Sv/hr, from 0 to 350,000 CPM, and from 0 to 5000 CPS. The Inspector EXP has a pancake-style detector, which connects via a BNC cable to the monitor (Fig. 3-6). It was calibrated in 2018 at the Colombian Geological Service using a beta Cs-137 radioactive source.
Radioactive sources (Fig. 3-7):

- **Fe-55:** This source was bought from Spectrum Techniques, Tennessee in September 2018. It has an activity of 10 µC, a half-life of 2.73 years, and it decays via electron capture into monoenergetic X-rays of 5.9 keV photon energy.

- **Sr-90:** This source was also bought from Spectrum Techniques but on 2012. It has an activity of 0.1 µC, a half-life of 28.8 years, and it undergoes beta decay into yttrium-90 with a decay energy of 0.546 MeV.

- **Tl-204:** This source was also bought from Spectrum Techniques on 2012. It has an activity of 1 µC, a half-life of 3.78 years, and it undergoes beta decay into Pb-204 with a decay energy of 0.764 MeV, and electron capture into Hg-204.

- **Am-241:** This source was bought on 2011. It has an activity of 1 µC, a half-life of 432.2 years, and it decays mainly via alpha decay of 5.48 MeV energy, with a weak gamma ray byproduct of 59.5 keV energy.

**Figure 3-7:** Am-241, Sr-90, Fe-55, and Tl-204 radioactive sources

- **Siemens Polymobil 10:** Portable X-ray source. Produces X-rays with a peak tube voltage from 40 to 125 kVp and a tube current from 0.1 to 100 mAs. Therefore, it includes the energies useful for diagnostic radiology (Fig. 3-8).
3.1.1. Electronic modules for signal processing

The CAEN NIM standard electronics crate is commonly used in high energy and nuclear physics experiments. At the laboratory, the following modules are available (see Fig. 3-9): [1]

- Ortec 452: Spectroscopy Amplifier. This is a double-width NIM module with user programmable gains from 0.5 to 3000. The shaping time, pulse polarity, output range, and delay can also be set. It has very low levels of noise, a wide gain range, and great overload response for high-resolution spectroscopy. It accepts input pulses of either polarity.

- N471: High voltage power supply. The output voltage ranges of each channel (automatic selection) are from 0 to ±3 kV / 3 mA or from ±8 / 1 mA (1 µA resolution). The output polarity can be independently selected for each channel.

- N405: Logic unit. Three independent sections that can be used either as an AND/OR
logic unit or a majority one. When only one input signal is enabled, the section acts as a logic FAN-OUT regardless of the AND/OR selected function.

- N979: Fast rise time amplifier. Housed in a 1-unit NIM module, each channel features a fixed voltage gain of 10. Fixed gain values from 2 to 9 are available on request by gain steps of 1. Channels can be cascaded in order to obtain larger gain values.

- N454: 4 independent Logic Fan In-Fan Out sections. Each section accepts 4 input NIM signals and performs on these the logic OR function.

- N841: 16 channel Leading Edge Discriminator. The module accepts 16 negative inputs and produces 16 NIM outputs + 16 complementary NIM outputs on 48 front panel LEMO 00 connectors. The Pulse Forming Stage of the discriminator produces an output pulse whose width is adjustable in a range from 5 ns to 40 ns per groups of 8 channels. Each channel can work both in Updating and Non-Updating mode according to the position of the on-board jumpers. The discriminator thresholds are settable in a range from -1 mV to -255 mV (1 mV step), via an 8-bit DAC (Digital to Analog Converter). The minimum detectable signal is -5 mV, and the maximum input voltage is 5V.

- N957: 8k Multi-Channel Analyzer (MCA) with USB port. The MCA analyzes a stream of voltage pulses and sorts them into a histogram of number of events versus pulse height, which may often relate to energy or time of arrival. It collects the data and produces an output in the form of the converted value of input peaks. They can range from 0 to 10 V, with a rise time greater than 0.1 µs. The MCA provides the necessary analog to digital conversion for a spectroscopic analysis of a detector’s signal.

- N8303: 5U Non ventilated NIM crate (19in 12 slot) available with both pluggable 300W and 600W power supplies.
3.1 Instruments and devices

- Canberra Model 512: Dual Counter/Timer. This module is also attached to the crate. It offers a count rate of more than 250 MHz, and its counters have a count capacity of \(10^{15}\). It is used for photon counting applications or experiments requiring pulse-pair resolutions as high as 4 ns (Fig. 3-10).

Although not part of the crate, the following electronic devices are also used:

- CAEN A 1422: Charge Sensitive Preamplifier. It has eight HV input and eight LEMO output channels. Its theoretical gain is 45 mV/MeV, and the capacitance of the detector input is less than 200 pF. Its main function is to receive the small signals directly from the detector and amplify them in terms of charge, before sending them off to the amplifier (Fig. 3-11).
LeCroy WaveSurfer 24MXs-B: 200 MHz oscilloscope. This oscilloscope handles large amounts of data quickly providing fast processing of long memory even when using math and measurement functions, and has a responsive user interface that works on Windows XP. Additionally, it has 18 digital channels and analog and digital cross pattern triggering. It has all of the usual properties of an oscilloscope, plus additional perks such as a USB port and the possibility to export data in multiple formats (Fig. 3-12).
3.1 Instruments and devices

- Keithley (Tektronix) Model 6485: Picoammeter. This ammeter can measure currents from 10 fA to 20 mA, at speeds up to 1000 readings per second. This model has a high resolution and 8 current measurement ranges from 20 mA down to the 2 nA range, with the 2 nA range having the lowest noise (Fig. 3-13).

![LeCroy WaveSurfer oscilloscope](image1)

**Figure 3-12:** LeCroy WaveSurfer oscilloscope

![Keithley picoammeter](image2)

**Figure 3-13:** Keithley picoammeter
3.2. **Summary of methodology**

To establish the functionality of the triple-GEM detector owned by CRYOMAG research group, all of the connections in the external voltage divider circuit were tested along with the readout voltage and current throughout it. Then it was evaluated if it was possible to obtain a signal on the oscilloscope when the voltage was increased enough for the gas to be ionized by either muons from cosmic rays, an X-ray tube, or a radioactive source. Peaks in the signal from the oscilloscope implied the detection of ionizing particles. Therefore, the detector was said to be working as expected.

Measurements were then taken for a wide range of voltages, varying between $-3700V$ and $-4575V$ with an uncertainty of $\pm 1V$ in steps of 25V, to find the range of functionality. A graph of voltage vs counts was made. This allowed an initial approximation into both the efficiency of the detector and its optimal operating voltage range.

The next step was characterization. First, typical signals for cosmic rays were studied using the oscilloscope. Characteristics such as amplitude, duration, shape, and polarity of pulses were measured and analyzed. The size of the background noise and range of operation before sparks appear was determined. Additionally, the voltage was varied in order to check that the triple-GEM detector recreated the expected characteristic curve of gaseous ionizing detectors, going through all of the expected regions (see Fig. 2-13). It was determined in which region the detector worked without generating sparks. Then, properties such as sensitivity, energy resolution, temporal resolution, efficiency, gain, and response to various sources were measured, according to the procedures explained in Section 2.4.

After characterization, the calibration process began. The triple-GEM detector was calibrated by recreating the spectrum of iron-55, which has a characteristic gamma emission line at 5.9 keV. A charge pre-amplifier was used to convert each pulse into a new pulse of amplitude equal to the collected charge. Then, using a multi-channel analyzer (MCA) a histogram of counts per channel was created, that looked like the spectrum of the radioactive source used. Knowing that the highest peak should be at the channel that represents the characteristic energy of that specific radioactive source (and that the spectrum also included peaks at channels that could be equated to the characteristic emission energies and escape energies of the gas used) allowed to calibrate channels on the MCA histogram.
3.2 Summary of methodology

to voltage at the specific parameters used.

Afterwards, dose measurements were taken and compared to measurements done with a conventional ionization chamber dosimeter used in medical physics. The possible dosimetry applications were determined based on the measured properties. The viability of GEM detectors as radiation dosimetry detectors was studied.
4 Results and analysis

Before starting to do measurements with the detector, physical adjustments were made to prepare it for its required use. The first thing that was done was to use a flat tinned copper braid to interconnect the grounds of all the electronic elements, including the high voltage supply, the triple-GEM detector, the oscilloscope, and the NIM modules. Without it, the electronic noise is so big that it overshadows any signal pulse.

Then, the voltage divider circuit was checked. In order to feed all electrodes with only one source, a voltage divider is used that distributes the original voltage between the anode and cathode and the negative and positive copper electrodes of each GEM foil (see Figure 4-1). Every triple-GEM detector can have its own configuration of resistors and capacitors. Usually, a capacitor is located at the beginning of the divider circuit to work as a low-pass filter and protect the detector from peaks of very high voltage. A second capacitor is located at the end of the divider circuit to work as a high-pass filter and allow only real signals to go through.

In Figure 4-1, the nominal values of all the resistors and capacitors from our detector’s unique voltage divider circuit are shown. These values were corroborated using a multimeter and all lie within the expected errors.

To further test the state of the voltage divider circuit, the high voltage supply was connected to it at the top left, where is says -HV. The polarity of the supply voltage needs to be negative so that the direction of the electric field generated between the electrodes leads the electrons towards the signal output.

A voltage of -4000V was supplied to the circuit, and a picoammeter was connected between resistor R3G and ground. The expected current at this location, due to the total resistance of the circuit, was $701.8\mu A$. The measured current gave $696 \pm 5\mu A$, which was close enough to suggest that the circuit was working as expected.

Then the voltages at each location shown in the circuit diagram were calculated from
Results and analysis

Figure 4-1: Voltage divider circuit for the triple-GEM detector

The supply voltage and the values of the resistors. These were used to find the theoretical voltages within each GEM foil, and the drift voltages between GEM foils. The former cause the acceleration of electrons inside the holes of the GEM foil, while the latter make the electrons drift from one foil to the next. The values found are displayed in table 4-1.
4.1 Typical signals

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VG1</td>
<td>-386.0</td>
</tr>
<tr>
<td>VG2</td>
<td>-350.9</td>
</tr>
<tr>
<td>VG3</td>
<td>-315.8</td>
</tr>
<tr>
<td>VD1</td>
<td>-701.8</td>
</tr>
<tr>
<td>VD2</td>
<td>-701.8</td>
</tr>
<tr>
<td>VD3</td>
<td>-701.8</td>
</tr>
</tbody>
</table>

Table 4-1: Voltages inside each GEM foil and between each drift region for the aforementioned voltage divider circuit of the triple-GEM detector.

As seen in Section 3.1, the basic setup of the triple-GEM detector includes a connection to a high voltage supply, a gas input regulated by a flowmeter, and signal outputs both at the strips and at the bottom of the third GEM foil (GEM3B output). Any or both of these signal outputs are then sent to the required electronics that depend on the specific application (see Fig. 4-2). In each of the following sections, a diagram with the specific electronics for each application will be shown.

Figure 4-2: Schematic diagram of the basic experimental setup showing the connections to the triple-GEM detector. The electronics depend on the specific application.
4.1. Typical signals

In order to test the functioning of the detector and the electronics, images were taken of typical, characteristic signals for both cosmic muons and the Fe-55 radioactive source. Depending on the signal output used to generate the pulses, their polarity was different. Every pulse taken from the strips output was negative, and every pulse taken from the bottom of the third GEM foil output was positive. A test was done to check that the results were equal on either output: each was connected on a different channel of the oscilloscope, and the OR function was used as trigger at $-17$ mV on the amplified negative channel and $1.7$ mV on the positive channel. Every single time it was triggered there was a signal on both channels. This means that it is correct to assume that the same results would be obtained with either signal output. Most results have been done using the bottom of the third GEM foil output so they have positive polarity.

Through these tests, it was learned that the average Fe-55 signal is 8-10 mV in height, and has a duration of 80 ns. They don’t vary much in shape or size, with most pulses having an amplitude of 8 mV and having a slightly faster fall time than rise time. The average muon signal is 1-10 mV in amplitude, and has a duration of 60-120 ns. They have considerably greater variance in shape and size than the Fe-55 signals. Additionally, they have a much more noticeable difference between rise time and fall time, with the rise time being smaller. For both radiation sources, the background noise level was very small, such that it can be taken as zero. Even at the lowest possible scale on the oscilloscope, the noise level rarely left the zero line (Figs. 4-4, 4-5).
4.1 Typical signals

Figure 4-4: Muon signals taken with the triple-GEM detector at a supply voltage of $-4250\text{V}$, a threshold of $1.5\text{mV}$, and a gas flow of $0.3\ \text{l/min}$. The horizontal time scale is $200\text{ns}$ per division, and the vertical voltage scale is $5\text{mV}$ per division. They were taken from the bottom of the third GEM foil output.

Figure 4-5: Fe-55 signal taken with the triple-GEM detector at a supply voltage of $-4202\text{V}$, a threshold of $8\text{mV}$, and a gas flow of $0.5\text{l/min}$. The horizontal time scale is $200\text{ns}$ per division, and the vertical voltage scale is $2\text{mV}$ per division. It was taken from the bottom of the third GEM foil output.
Figure 4-6: X-ray signal from the triple-GEM detector at a supply voltage of -3700V, a tube current of 64mAs, a peak tube voltage of 46kVp, and an SOD of 83cm, taken from the strips output. No amplification was used. The horizontal time scale is 2ms per division, and the vertical voltage scale is 10mV per division.

X-ray signals obtained from the Siemens Polymobil 10 portable X-ray machine vary depending on the supply voltage, the SOD (source to object distance), the tube current, and the peak tube voltage. The last two are user settings programmable on the X-ray machine, and the amplitude of the signal on the oscilloscope is proportional to all. It can be seen that the greater the supply voltage, the taller the biggest peak (Figs. 4-6, 4-7). The signals have an amplitude ranging from 10-40 mV, a duration ranging from 5ms-1µs, and a very distinctive shape in which the peaks get shorter and shorter to the right, in a sort of oscillating manner.
4.2 Optimal functioning parameters

Figure 4-7: X-ray signal from the triple-GEM detector at a supply voltage of -4350V, a tube current of 64mAs, a peak tube voltage of 46kVp, and an SOD of 83cm, taken from the strips output. No amplification was used. The horizontal time scale is 2ms per division, and the vertical voltage scale is 10mV per division.

4.2. Optimal functioning parameters

Figure 4-8: Schematic diagram of the experimental setup used to obtain the optimal functioning parameters of the triple-GEM detector.
Supply voltage

The first data that was taken in order to determine the optimal functioning parameters for the triple-GEM detector was measurements of voltage versus counts. For muons, the detections started at $-3775\text{V}$. The first spark occurred at $-4375\text{V}$ and a second at $-4500\text{V}$, but since there were no constant sparks the voltage was increased even further, up to $-4575\text{V}$ without any continuous discharges. However, the voltage can only be increased as such if there is no radioactive source on the detector. If the Fe-55 source is put near it at such high voltages, there will immediately be constant sparks.

The muon graph, Figure 4-9, shows an unexpected behavior. Apart from a decrease in counts at around $-4350\text{V}$ of unknown origin, the efficiency seems to increase constantly and exponentially with voltage, even at very high voltages at which normally there are sparks. Since it never reaches a stable value, it would seem that the efficiency is highest for cosmic muons at the highest possible supply voltage before sparks occur. Also, the theoretical value of 187 muons per minute was reached only at the highest voltages, from around $-4250\text{V}$ onward.

For voltage versus counts with the Fe-55 source, the graphs in Fig. 4-10 do experience the behavior that is expected: the number of counts increases with voltage up to a stabilization point after which the efficiency doesn’t really increase too much. When making the graph on the right, there were no loud sparks, but from $-4275\text{V}$ onward the count started increasing. When it was looked at on the oscilloscope, it was no longer the constant-height pulses that represent Fe-55 but a constant count that looked like noise, so the measurements were stopped at that voltage. It is apparent that the best voltage is about $-4200\text{V}$, which is somewhere in the middle of the plateau. Therefore, future tests and experiments were done at a supply voltage of $-4325\text{V}$ for muons, and a supply voltage of $-4200\text{V}$ for Fe-55.

Since radioactive decay can be described by a Poisson distribution, the standard deviation (which is then used for error bars) is given by $\sigma(\hat{\mu}) = \sqrt{\bar{x}/n}$ [19]. If each value is measured only one time, $n = 1$ and $\bar{x} = x$, so the error bar is $\sqrt{x}$ where $x$ represents each of the measurements.
4.2 Optimal functioning parameters

Figure 4-9: Counts vs Supply voltage graphs for cosmic muons with the triple-GEM detector. Left: Signal taken from the strips output (negative polarity), and amplified x10. Threshold = -17mV. Right: Signal taken from the bottom of the third GEM foil output (positive polarity) and with no amplification. Threshold = 1.3mV. This graph was made to show the relationship between detection efficiency and supply voltage for cosmic muons. Detections started at $-3775\text{V}$ and there were sparks at $-4375\text{V}$. The theoretical value of 187 muons per minute was reached only at the highest voltages, from around $-4250\text{V}$ onward. Because of the exponential behavior with voltage, the efficiency is highest for cosmic muons at the highest possible supply voltage before sparks occur.
Figure 4-10: Counts vs Supply voltage graphs for the Fe-55 source with the triple-GEM detector. Left: Signal taken from the strips output (negative polarity), and amplified x10. Threshold = -17mV. Right: Signal taken from the bottom of the third GEM foil output (positive polarity) with no amplification. Threshold = 2.0mV. This graph was made to show the relationship between detection efficiency and supply voltage for Fe-55. The behavior is as expected: the count increases with voltage up to a stabilization point after which the efficiency plateaus. The second increase in the graph on the right is due to sparks, not greater efficiency. The voltage of maximum efficiency is $-4200\text{V}$, which lies in the middle of the plateau.
4.2 Optimal functioning parameters

Threshold

**Figure 4-11:** Counts vs Threshold graph for cosmic muons at a supply voltage of -4350V with the triple-GEM detector. The signals were taken from the bottom of the third GEM foil output with no amplification. Right: Close-up on the plane part of the graph on the left. This graph was made to show the relationship between detection efficiency and threshold for cosmic muons. At low thresholds there are very high levels of noise. After 0.5mV the number of counts stabilizes. Anything between 0.7 and 2mV gives a good efficiency.

Next, data was taken for trigger threshold versus counts for muons at −4350V and 2mV/div. In the graphs of Figure 4-11 it can be seen that after 0.5mV the number of counts is pretty much stable, at least compared to the very high levels of noise that can be seen at low thresholds. In the close-up graph, however, it is evident that there is a downward trend as the threshold is increased. No real stabilization is reached. Still, the shape of the original graph is very similar to the one done with Fe55 (Figure 4-12), with a big noise peak at the beginning and a long stabilization afterwards, that slowly leads to zero counts when the trigger is set way too high. Looking at the graph, anything between 0.7 and 2mV could work, so the trigger threshold chosen for muons for posterity was 1.3mV.

The same counts versus threshold graph was done for the Fe-55 source at −4202V without amplification (Figure 4-12). The channel on the oscilloscope was initially set to 2mV/div (black squares), and it was kept that way until the maximum threshold of 8mV.
From then on, it was set to 5mV/div (red dots) so that the threshold could be increased further. Then some other data points were taken at that division around the area when the big decrease starts to occur, and it was evident that the count is higher with the 5mV/div than with the 2mV/div even at the same threshold. That had to be taken into account when the threshold was determined in other experiments.

It is evident from the graph that the noise disappears after 0.4mV, so the count stabilizes. The trigger is too high after 4mV, when the count starts to decrease slowly. Therefore, the best possible thresholds for the Fe-55 source at $-4202\text{V}$ are anything between 0.5 and 4mV. The trigger threshold chosen for Fe-55 for posterity was 2mV.

**Gas flow**

Finally, gas flow versus counts graphs were done with the triple-GEM detector. Data was taken with muons, increasing the gas flow from 0 to 0.55 l/min (the maximum that the flowmeter takes). After every change in gas flow was made, one minute was counted before taking data at that new flow so that it could stabilize inside the detector. Everything was going normally until at 0.3 l/min there was a spark, and the counts increased unexpectedly. When more sparks started occurring, the measurements had to be stopped immediately. To fix this, the voltage was decreased down to $-4252\text{V}$, and both outputs from the detector were used with the logic AND to increase the chances of getting actual muons. The result is the graph of Fig. 4-13.

From this graph it looks like the greater the gas flow, the greater the number of counts, which would imply that efficiency increases with gas flow. However, there are too few data points and with too big errors for it to be reasonable to make conclusions. Therefore, the same measurement was attempted for the Fe-55 source (Fig. 4-14).

In this new measurement, it can be seen there is a sort of plateau after 0.25l/min, where the efficiency doesn’t change much with small changes in gas flow. This is good because it means that as long as the gas flow stays above that value, all measurement will remain reliable. Below this value, the gas flow is so small that there is no renewal of gas after ionization, so there are almost no counts. Therefore, a gas flow of 0.3 l/min was chosen for future tests with all sources because it doesn’t affect the efficiency of the detector but it does save gas and increases the durability of the gas tank.
4.2 Optimal functioning parameters

Figure 4-12: Counts vs Threshold graph for the Fe-55 source at a supply voltage of -4202V with the triple-GEM detector. The signals were taken from the bottom of the third GEM foil output with no amplification. This graph was made to show the relationship between detection efficiency and threshold for Fe-55. The oscilloscope’s voltage scale was initially set to 2mV/div (black squares), and it was kept that way until the maximum threshold of 8mV. From then on, it was set to 5mV/div (red dots) so that the threshold could be increased further. The noise disappears after 0.4mV, so the count stabilizes. The trigger is too high after 4mV, when the count starts to decrease slowly. Therefore, the thresholds with best efficiency for the Fe-55 source at −4202V are anything between 0.5 and 4mV.
Figure 4-13: Counts vs Gas flow graphs for cosmic muons at a threshold of 1.3mV and a supply voltage of -4252V with the triple-GEM detector. The signals were taken from the bottom of the third GEM foil output with no amplification. This graph was made to show the relationship between detection efficiency and gas flow for cosmic muons. It can be seen that the greater the gas flow, the greater the number of counts, which would imply that efficiency increases with gas flow. However, there are too few data points and with too big errors for it to be reasonable to make conclusions.
4.2 Optimal functioning parameters

Figure 4-14: Counts vs Gas flow graphs for the Fe-55 source at a threshold of 2.0mV and a supply voltage of -4200V with the triple-GEM detector. The signals were taken from the bottom of the third GEM foil output with no amplification. This graph was made to show the relationship between detection efficiency and gas flow for Fe-55. There is a plateau after 0.25l/min, where the efficiency doesn’t change much with small changes in gas flow. As long as the gas flow stays above that value, all measurement will remain reliable. Below this value, the gas flow is so small that there is no renewal of gas after ionization, so there are almost no counts. Therefore, the ideal gas flow to optimize efficiency and reduce costs is 0.3 l/min.
Summary of optimal parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Muons</th>
<th>Fe-55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>-4325V</td>
<td>-4200V</td>
</tr>
<tr>
<td>Threshold</td>
<td>1.3mV</td>
<td>2.0mV</td>
</tr>
<tr>
<td>Gas flow</td>
<td>0.3 l/min</td>
<td>0.3 l/min</td>
</tr>
</tbody>
</table>

Table 4-2: Optimal functioning parameters obtained for both muons and the Fe-55 radioactive source, with data taken from the bottom of the third GEM foil output.

4.3. Energy resolution

![Figure 4-15](image)

Figure 4-15: Schematic diagram of the experimental setup used to obtain the energy resolution of the triple-GEM detector and the spectrum of Fe-55.

In order to obtain the spectrum of the Fe-55 radioactive source, the triple-GEM detector (operated at $-3890V$ and a gas flow of $0.3l/min$) was connected to the preAmplifier, which was then connected to the ORTEC spectroscopy amplifier at an amplification of x10, a shaping time of $6.0\mu s$, and an output range of $-3V$. This signal was sent to the multichannel analyzer, which made the spectrum on the computer through a USB cable. The spectrum on Figure 4-16 resulted.

In this spectrum, two peaks are evident: a tall one centered around channel 2203, and a small one centered around channel 1079. This is exactly what is expected from the spectrum of Fe-55: the characteristic peak should be tall and on the right of a smaller peak, called the gas escape peak. Because the energies of both peaks are well documented,
4.3 Energy resolution

Figure 4-16: Spectrum of Fe-55 taken with the triple-GEM detector, a preAmplifier, a Spectroscopic Amplifier, and a Multichannel Analyzer, at a supply voltage of $-3890\text{V}$, a gas flow of $0.3 \text{l/min}$, and an amplification of $x10$. The small peak on the left is the argon escape peak, at a theoretical energy of $2.94\text{keV}$, and the peak on the right is the Fe-55 characteristic peak, at an energy of $5.9 \text{keV}$. The latter has an FWHM of 430 channels.

It was possible to correlate channel number to energy. The characteristic peak of Fe-55 lies at $5.9 \text{keV}$, and the gas escape peak is given by the energy of the emitted photoelectrons: $E_{p.e.} = E_\gamma - E_{K_\alpha} = 5.9 - 2.96 = 2.94 \text{keV}$ [32]. This results in the following equation:

$$\text{Energy (keV)} = 0.00263 \cdot \text{Channel} + 0.0985 \tag{4-1}$$

This implies that every channel on the oscilloscope has an energy of $0.00263 \text{keV} = 2.63 \text{eV}$. Additionally, channel zero has an offset of $0.0985 \text{keV} = 98.5 \text{eV}$.

With this information, the energy resolution $R$ can be calculated:

$$R = \frac{\text{FWHM}}{E} \tag{4-2}$$
where FWHM is the width of the peak at half of its maximum and \( E \) is the position of the peak, channel 2203 = 5.9 keV. In the spectrum, the peak has a height of 371 counts. This means that half of the maximum is around 186 counts. At that height, the Fe-55 characteristic peak has a width of 430 channels = 1.132 keV, which is the FWHM. Therefore, the energy resolution of the detector is

\[
R = \frac{430}{2203} = 0.195 = 19.5\% \tag{4-3}
\]

This resolution agrees very well with that mentioned in literature for the triple-GEM detector, which is 20\% [27]. Even though the result is as expected, this energy resolution is not very good compared to other detectors that are specifically used for spectrometry, which could have resolutions of up to 1\%. This explains why it was hard to obtain good spectra for other radioactive sources and for X-rays. However, what this detector lacks in energy resolution it complements with excellent temporal resolution, spatial resolution (with the correct electronics), and gain.

### 4.4. Temporal resolution

![Figure 4-17](image.png)

*Figure 4-17: Schematic diagram of the experimental setup used to obtain the temporal resolution of the triple-GEM detector using the exponential attenuation law.*

The intrinsic temporal resolution, which depends on the length and quality of the cables, the speed and dead time of the electronics, and the intrinsic retardation of the detector due to the diffusion of charges inside it and the speed of formation of the signal in the electrodes, can be approximated by measuring the width of the thinnest pulses on the oscilloscope. This value was obtained from the smallest muon pulses (at a supply voltage of -4200V, a gas flow of 0.3 l/min, and a threshold of 2mV), and gave 40ns. No matter
the radiation source, every electronic device has its own intrinsic temporal resolution that limits how fast a pulse can be detected after another one and be distinguishable from it.

Another way to get a sense of the dead time of the detector, or how long it takes for it to be ready to make a second detection after one was made, is by measuring the smallest horizontal distance between two pulses on the oscilloscope (see Fig. 4-18). For the Fe-55 radioactive source, more than 200 signals were analyzed and the smallest time found was 8\(\mu\)s. This is not an exact temporal resolution either, but it does give a measure of how quickly the triple-GEM detector is ready to make another detection; in other words, how long its dead time is.

![Figure 4-18: Two consecutive Fe-55 pulses taken on the triple-GEM detector at a supply voltage of -4200V, a gas flow of 0.3 l/min, and a threshold of -2mV. The horizontal scale is 2\(\mu\)s per division and the vertical scale is 2mV per division. It was taken to measure the shortest time it takes for the triple-GEM detector to be ready to detect a new pulse after a detection. For the Fe-55, this time was found to be 8\(\mu\)s. The signal was taken from the strips output with no amplification.](image)

A basic principle of physics that can help determine if there is saturation either at
the triple-GEM detector, the oscilloscope, or the counter that could decrease the temporal resolution is the exponential attenuation law. It states that the reduction in intensity of radiation as it crosses a medium can be described by an exponentially decaying function, whose parameters depend on the characteristics of the medium (see Sec. 2.7.1). However, if a detector gets saturated at high intensities, the graph would only appear to decay exponentially at high filtration, when less radiation reaches it. Therefore, tests were done with the Fe-55 source to check for saturation in the triple-GEM, using 2cm x 2cm aluminum foil sheets, at a 2mV threshold on the bottom of the third GEM foil output (AND a -1.3mV threshold on the strips output for extra confidence), a high voltage of -4200V, and the maximum gas flow (0.55 l/min). The results, as well as the exponential decay fit, are shown in the graph of Fig. 4-19.

From these results, because the fit has an R-squared value of more than 0.99, it can be said that the relationship between the Fe-55 counts and the width of aluminum filtering is that of an exponential decay, which is what is expected theoretically. Because there is no plateau at the beginning, it is evident that there is no count saturation neither in the detector nor in the oscilloscope or counter.

Additional tests for temporal resolution were done with the portable X-ray machine. It was set at the maximum peak tube voltage (125kVp) and the triple-GEM detector was set at the maximum supply voltage before sparks occur (-4300V). Then, the tube current was varied from 0.4 to 50mAs (the maximum) to see if there was any saturation. The pulses were studied on the oscilloscope and there was never any evidence of saturation at all; they kept increasing in size with the tube current and had no cutoff at their maximum amplitude. This implies that the detector has no problem measuring the maximum photon rate of the portable X-ray machine, which uses the standard parameters of radiological machines.

It is not possible to determine the saturation from the number of counts in each signal because each pulse registers as a single count. Therefore, the temporal resolution with the X-ray machine can only be determined qualitatively.
4.5 Efficiency

Even though there is no saturation in the number of counts, that doesn’t mean that the efficiency of the detector is 100%, because the whole counts graph could be a factor below the actual number of counts. In order to check this, the number of counts of every available radioactive source was compared to the theoretical activity and to the activity measured by the Inspector Geiger-Muller detector.

The theoretical activity of a radioactive source is given by the equation:
Figure 4-20: Schematic diagram of the experimental setup used to obtain the efficiency of the triple-GEM detector. Even though it was attempted to measure the activity of the sources using the counter, it was impossible to obtain a sensible result with it, and it was determined that the most accurate result was that coming from the oscilloscope’s trigger counter.

\[ I = I_0 e^{-t/t_{1/2}} \]  

(4-4)

where \( I_0 \) is the original activity of the source, \( t \) is the time that has passed since it was made, and \( t_{1/2} \) is its half-life. Since this activity is for a solid angle of \( 4\pi \) (the sources radiate equally in all directions) but a flat detector can only detect the lower hemisphere, the expected activity was obtained by dividing \( I \) into two. The results are in Table 4-3.

<table>
<thead>
<tr>
<th>Source</th>
<th>Activity (( \mu )Ci)</th>
<th>Time (yrs)</th>
<th>Half-life (yrs)</th>
<th>Expected Activity (CPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-55</td>
<td>10</td>
<td>0.71</td>
<td>2.73</td>
<td>8,569,447</td>
</tr>
<tr>
<td>Sr-90</td>
<td>0.1</td>
<td>6.9</td>
<td>28.8</td>
<td>87,352</td>
</tr>
<tr>
<td>Tl-204</td>
<td>1</td>
<td>6.9</td>
<td>3.78</td>
<td>178,881</td>
</tr>
<tr>
<td>Am-241</td>
<td>1</td>
<td>7.9</td>
<td>432.2</td>
<td>1,089,895</td>
</tr>
</tbody>
</table>

Table 4-3: Expected activity for each of the radioactive sources in the laboratory for a solid angle of \( 2\pi \)

The activity of each source was then measured with both the triple-GEM and the Inspector detectors, and each of their efficiencies was determined according to the expected activity. Additionally, the relative efficiency of the triple-GEM compared to the Inspector was calculated. These results are shown in Table 4-4. The triple-GEM was used at a supply voltage of \(-4200\)V, a trigger of \(2\)mV, and a gas flow of \(0.3\) l/min. The background on the
4.5 Efficiency

Table 4-4: Efficiencies of the triple-GEM and Inspector detectors compared to the theoretical expected activity and relative efficiency of the triple-GEM compared to the Inspector detector.

<table>
<thead>
<tr>
<th>Source</th>
<th>Triple-GEM count (CPM)</th>
<th>Inspector count (CPM)</th>
<th>Triple-GEM efficiency</th>
<th>Inspector efficiency</th>
<th>GEM vs Inspector relative efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-55</td>
<td>15,750</td>
<td>92,807</td>
<td>0.18 %</td>
<td>1.1 %</td>
<td>17.05 %</td>
</tr>
<tr>
<td>Sr-90</td>
<td>11,155</td>
<td>232,500</td>
<td>12.8 %</td>
<td>266.2 %</td>
<td>4.8 %</td>
</tr>
<tr>
<td>Tl-204</td>
<td>3,775</td>
<td>41,500</td>
<td>2.1 %</td>
<td>23.2 %</td>
<td>9.1 %</td>
</tr>
<tr>
<td>Am-241</td>
<td>4,225</td>
<td>280,000</td>
<td>0.4 %</td>
<td>25.7 %</td>
<td>1.5 %</td>
</tr>
</tbody>
</table>

Table 4-4: Efficiencies of the triple-GEM and Inspector detectors compared to the theoretical expected activity and relative efficiency of the triple-GEM compared to the Inspector detector.

Inspector was $50 \pm 2$ CPM, while the background on the GEM detector gave $96 \pm 5$ CPM.

These results have the issue that every detector’s sensitivity is different, and each detector is calibrated with a specific type of radiation. Therefore, there is no constant efficiency of the triple-GEM compared to the Inspector. According to Inspector’s manual, its efficiency with an Sr-90 source is 38%, while with an Am-241 it is 18%. It is evident that the triple-GEM detector works best to detect Sr-90 in terms of absolute efficiency, but it has the best relative efficiency compared to the Inspector detector with the Fe-55 source. This is due to the fact that the Inspector detector was not made for radioactivity of energies as low as that of Fe-55, because they are not useful in most applied fields. The Inspector has greater efficiencies with sources of higher energies and higher activities. It could be that if it had been possible to measure the activity of the sources with the triple-GEM detector connected directly to the counter, the efficiencies would have been a lot higher, even more so than the reference detector’s efficiency. However, enough data was taken to understand with which radioactive sources the GEM works best. It is left for the near future to study how the reliability of these efficiency measurements can be improved using other electronic equipment.

In order to get the efficiency of the triple-GEM detector for cosmic muons, the background radiation was measured with the Inspector detector in five different locations of the laboratory for 20 minutes each. Because muon flux does not change from one corner of a room to the other, anything above the lowest count is probably background contamination, which can be caused by sunlight or other external sources of radiation. The measurements
gave $55 \pm 2$, $50 \pm 2$, $50 \pm 2$, $53 \pm 2$, and $52 \pm 2$ CPM. The highest count was taken beside the window, when sun was coming in. The lowest counts were taken at darker places. Therefore, it was determined that that minimum value of $50 \pm 2$ CPM was the actual muon count of the Inspector detector.

The background count with the triple-GEM detector was taken ten different times with a gas flow of $0.3 \text{ l/min}$, a $1.3 \text{mV}$ trigger, and a supply voltage of $-4400 \text{V}$. The result was $283 \pm 7$ CPM.

Because the active area of the Inspector detector has a diameter of $5 \text{cm}$, it has an area of $19.6 \text{cm}^2$. This means the GEM, with an active area of $100 \text{cm}^2$, should have $5.1$ times the number of muon counts than the Inspector, which gives $255 \pm 10$ CPM. This is even less than what the actual muon count was on the triple-GEM detector, which means it has an efficiency of $111\%$ with respect to the Inspector detector in detecting muons. The muon counts are also higher than what is expected from the theoretical $1.87$ muons per minute per square centimeter, giving $2.83$ muons with the triple-GEM and $2.55$ with the Inspector. Since this $1.87$ is just an approximation, and not an actual measurement, this could either mean that the real muon flux at the laboratory is higher than what theory predicts, or that neither detector is correctly calibrated for cosmic muon detection. Either way, it is clear that the triple-GEM is most sensitive towards cosmic radiation. This makes sense, since GEM detectors were designed for high energy physics experiments specifically to detect muons resulting from particle collisions. Low energy particles can get absorbed by the different layers that make up the triple-GEM detector, such as the kapton cover on top of the active area, attenuating the radiation before it can be detected. Geiger Muller detectors, instead, can detect lower energy particles with ease. This was all corroborated during these tests.

It would have been more precise to measure the triple GEM’s efficiency for detecting muons using the telescopic arrangement of scintillators and photomultipliers explained in Section 2.4.5. However, multiple tests and adjustments were made to them over a period of three months trying to obtain sensible results, but it was not possible. Part of CRYOMAG research group’s pending tasks are to carry out any additional testing and determine how to make having a pair of scintillators and photomultipliers a possibility for future projects. But as far as this thesis goes, the best was done with what was available at the time.
4.6 Gain

In order to calculate a detector’s gain, the output current needs to be measured. For the triple-GEM detector, there are four strips outputs, two in each direction, that should be connected in parallel. However, because there are only two connectors for these four outputs, the two connectors at the bottom of the detector (called here left and right strips outputs) were chosen for the current measurements. Because about half of the charge must reach the strips on the bottom and the other half the strips on the side, the measured current was multiplied by two in order to obtain the output current used in gain calculations.

With this in mind, a voltage vs current graph was done with the Keithley picoammeter. The Fe-55 source was placed on the center of the detector, and the left and right strips were connected in parallel to the picoammeter. The supply voltage was varied from -3600V to -4400V, and the gas flow was set to 0.3 l/min. Measurements were stopped at -4400V because at that point there were countless sparks, so the voltage had to be decreased. There was a big variance in the current measurements, which can be seen in the error bars of the graph. Yet, the current follows the exponential behavior with supply voltage expected from a radioactive source. The current without a source does increase with voltage but at much lower values. The output current is the result of subtracting the current with the Fe-55 source minus the current without the source (see Figure 4-22).

From the output current, the gain can be calculated in the following way:

$$G = \frac{\text{collected charge}}{\text{primary charge}} = \frac{I}{f \cdot e \cdot n} \quad (4-5)$$

where the current $$I = 2 \cdot I_{\text{output}} = 2 \cdot (I_{\text{with source}} - I_{\text{without source}})$$, $$f$$ is the measured
Figure 4-22: Current vs Supply voltage with the Fe-55 source, with the left and right strips outputs connected in parallel. The gas flow was set to 0.3 l/min, and the supply voltage was varied from -3600V to -4400V. This graph was made to measure the output current needed to calculate the detector’s gain. The current due to the source, called output current, is the result of subtracting the current with the Fe-55 source minus the current without the source. It follows the exponential behavior with supply voltage expected from a radioactive source.

activity of the source (number of particles that cross the detector per second), \( e \) is the elementary charge, and \( n \) is the number of primary electrons produced by a single incident particle. The gain was plotted for the activity of the source measured with the triple-GEM detector, \( f = 262 \pm 16 \text{ CPS} \). It was found by converting the values on Table \([4-4]\) from CPM to CPS. The gain of the triple-GEM detector must be calculated with its own count rate, since that gives the actual number of photons that deposited all their energy in it.

In order to calculate the number of primary electrons produced, the energy absorbed by the medium had to be determined. To do this, the cross sections of photon interactions
for 5.9 keV photons were looked up on NIST tables for the specific gas mix used in the detector (Ar 75% - 25% CO₂). They were as follows: \( \sigma_R = 1.027 \text{ cm}^2/\text{g} \), \( \sigma_C = 0.07718 \text{ cm}^2/\text{g} \), \( \sigma_{pe} = 208.5 \text{ cm}^2/\text{g} \), and \( \sigma_{pp} = 0 \text{ cm}^2/\text{g} \). Being 99.5% of the total cross section, the photoelectric effect is the clearly dominant process, two orders of magnitude more prominent than the second most common photon interaction. In photoelectric effect, there is a complete absorption of the incident photon \( (E_e^− = E_γ − E_B) \), and the binding energy \( E_B \ll E_γ \). Therefore, an absorbed energy of 5.9keV can be assumed, since in most cases the total energy of the photon is used to produce primary electrons while crossing the drift region \([59, 78]\). This value of energy gives a number of primary electrons of \( n = \frac{E_{Fe-55}}{W_{Ar-CO₂}} = \frac{5900 \text{ eV}}{27.5 \text{ eV}} \approx 214 \) (see Eq. 2-56 for \( W_{Ar-CO₂} \)).

Using these values, a supply voltage vs gain graph was made in Figure 4-23.

In this graph, it can be seen that the relationship between supply voltage and gain is almost linear, as expected. According to most of the articles studied, the gain of a triple-GEM detector lays between \( 10^3 - 10^5 \) as the supply voltage is increased. However, the highest possible gain obtained was above that range:

\[
G = \frac{I}{f \cdot e \cdot n} \approx \frac{2 \cdot (21.32 \pm 4.5) \times 10^{-9} \text{ A}}{262 \pm 16 \text{ s}^{-1} \cdot 1.602 \times 10^{-19} \text{ C} \cdot 214} \approx (4.7 \pm 1.3) \times 10^6 \tag{4-6}
\]

In order to test the validity of this calculation made with the Fe-55 source, but now with cosmic muons, a voltage versus current graph was made at the same voltage range (see Fig. 4-24). At first sight, the graph is as expected: an exponential relation between voltage and current even for a source of such low intensity. Next, the muon intensity at the laboratory was calculated using this graph. A voltage of \(-4350\text{V}\) was chosen for the test, since this value is the one that works best for muon detection. Using the gain calculated at that voltage with Fe-55, the muon activity was computed. To do this, the current produced by muons was taken from the graph and the number of primaries was calculated using the stopping power of minimum ionizing particles (MIPs) in an Ar-CO₂ mix for the energy deposited by each entering muon.

\[
n = \frac{E_{muons}}{W_{Ar-CO₂}} = \frac{(dE/dx)_{MIPs} \cdot x}{W_{Ar-CO₂}} = \frac{(2440 \text{eV/cm} \cdot 0.75 + 3010 \text{eV/cm} \cdot 0.25) \times 0.9 \text{cm}}{27.5 \text{ eV}} = 84.5 \tag{4-7}
\]
Results and analysis

Figure 4-23: Gain vs Supply voltage with the Fe-55 source plotted in a logarithmic scale, using the count rate $f$ of the triple-GEM detector. This graph was made calculating the gain from the measured current, the saturation value of the activity of the Fe-55 source, and the number of primary electrons produced. The relationship between supply voltage and gain is almost linear on a logarithmic scale, as expected. The highest possible gain obtained was $(4.7 \pm 1.3) \times 10^6$.

where $x$ is the depth of gas. The $(dE/dx)_{MIPs}$ is given by a weighted average of the $dE/dx$ for argon (2440 eV/cm) and for carbon dioxide (3010 eV/cm), with the values given in Table 2-5. With this $n$, the number of muons entering the detector each second was calculated:

$$f = \frac{I}{G \cdot e \cdot n} = \frac{2 \times 0.28 \times 10^{-9} \text{ A}}{4.75 \times 10^6 \cdot 1.602 \times 10^{-19} \text{ C} \cdot 84.5} = 8.71 \pm 3.1 \text{ CPS} = 522 \pm 186 \text{ CPM}$$

(4-8)

$522 \pm 186$ counts per minute is minimum 1.2 times the muon count measured on the triple-GEM detector, of $283 \pm 7 \text{ CPM}$. Because these measurements were taken on
4.7 Characteristic response curve

Figure 4-24: Current vs Supply voltage for cosmic muons at the left and right strips outputs connected in parallel. This graph was made to test the validity of the Fe-55 gain calculation, but with cosmic muons. It is as expected: an exponential relation between voltage and current even for a source of such low activity.

different days (and cosmic showers are a possibility), the gain has an exponential behavior with voltage, and both gain and current have errors, this result is not at all bad. Therefore, it was determined that the gain calculation is correct, at least in order of magnitude, when done with the triple-GEM count rate.

4.7. Characteristic response curve

The characteristic response curves of gaseous detectors are graphs of supply voltage vs charge collected, plotted on a logarithmic scale. The number of charges was determined from the collected current data obtained before, and this was graphed in Fig. 4-26 in order to identify in which region the triple-GEM detector was working (see Section 2.5.4).
Figure 4-25: Schematic diagram of the experimental setup used to obtain the characteristic response curve of the triple-GEM detector.

Figure 4-26: Number of charges collected per second vs Applied voltage with the Fe-55 source graphed on a logarithmic scale. This graph recreates the proportional counter region of the characteristic response curve for gaseous detectors. In this region, the counts are proportional to the energy deposited by incoming particles.
4.7 Characteristic response curve

Figure 4-27: Number of charges collected per second vs Applied voltage with cosmic muons graphed on a logarithmic scale. This graph also recreates the proportional counter region of the characteristic response curve for gaseous detectors, just like with the Fe-55 source, but with greater errors.

As can be determined from Figures 4-26 and 4-27, the graphs are almost linearly increasing. This means that the triple-GEM detector is working at the proportional counter region to detect both the Fe-55 source and cosmic muons (see Sec. 2.5.4). In this region, the counts are proportional to the energy deposited by incoming particles. The fact that the detector is working in this region is satisfactory, not only because the gain is expected to be between $10^4$ and $10^6$ (see Sec. 2.5.4) and that was the obtained result, but also because it means that the size of the charge pulses can be directly related to the energy of the incoming particles, so absorbed dose can be calculated.

The Fe-55 counts graph done with aluminum filters in Fig. 4-19, which demonstrated the exponential attenuation law, can be used to show the linearity of the detector’s response as a function of the intensity of the photon beam reaching it. The same data was plotted using a logarithmic scale for counts, and gave the graph in Fig. 4-28.
4.8. Dosimetry

As was seen in Section 2.7.1, the absorbed dose is defined as the energy $dE$ absorbed by a volume of mass $dm$ of a medium:

**Figure 4-28:** Counts plotted on logarithmic scale vs Thickness of aluminum filters, taken on the triple-GEM detector at a supply voltage of -4200V, a threshold of 2.0mV, and a gas flow of 0.55l/min. It shows the linearity of the detector’s response as a function of the intensity of the photon beam reaching it. The response with photon beam intensity does increase linearly, since the greater the thickness of aluminum filters, the smaller the intensity of the incident beam.

It can be seen that the triple-GEM detector’s response with photon beam intensity does increase linearly, since the greater the thickness of aluminum filters, the smaller the intensity of the incident beam. This behavior is just as expected.
\[ D_{med} = \frac{dE}{dm} \] (4-9)

In the case of the triple-GEM detector, \( dm \) is equal to the total mass of gas inside the active area, given by the effective density times the volume of gas.

The effective density of the Ar-CO\(_2\) gas mix is the weighted average of the densities of each of the components:

\[
\rho = 0.75 \cdot \rho_{Ar} + 0.25 \cdot \rho_{CO_2} = 0.75(1.652 \times 10^{-3}) + 0.25(1.827 \times 10^{-3}) = 1.696 \times 10^{-3} \text{g/cm}^3
\] (4-10)

The volume of gas can be calculated from the dimensions of the active area. The length and width are both 10cm. For depth, the drift gap is 3mm, both transfer gaps are 2mm, and the induction gap is also 2mm. That gives a volume of:

\[
V = 10 \times 10 \times (0.3 + 0.2 + 0.2 + 0.2) \text{ cm}^3 = 90 \text{ cm}^3
\] (4-11)

So the mass of gas inside the detector is:

\[
dm = \rho \times V = 1.696 \times 10^{-3} \text{ g/cm}^3 \times 90 \text{ cm}^3 = 0.153 \text{ g} = 0.153 \times 10^{-3} \text{ kg}
\] (4-12)

The absorbed energy \( dE \) was found using different methods depending on the radiation source and available data.

### 4.8.1. Measuring dose from the Fe-55 source

**Dose from current**

In Section 4.6, the current generated by the Fe-55 radioactive source was measured at various applied voltages. When the amount of charge produced through primary gas ionizations \( Q_{prim} \) is known, the absorbed dose can be calculated from the following equation (see Sec. 2.7.4):

\[
D_{det} = \frac{Q_{prim}}{dm} \left( \frac{W_{Ar-CO_2}}{e} \right)
\] (4-13)
From equation [2-56], it is known that \( W_{Ar-CO_2} = 27.5 \text{eV} \), so \( (W/e) = 27.5 \text{V} = 27.5 \text{J/C} \). The measured current at an applied voltage of \(-3890 \text{V}\) was \((1.45 \pm 0.57) \times 10^{-9} \text{C/s}\) (from Fig. 4-22). At that voltage, the gain is about \(3.2 \times 10^5\). The measured current should be around one fourth of the total current produced after multiplication, because it came from only one of the four strips outputs. This gives:

\[
Q_{prim} = \frac{Q_{total}}{G} = \frac{4 \cdot (1.45 \pm 0.57) \times 10^{-9} \text{C/s}}{3.2 \times 10^5} = (1.81 \pm 0.71) \times 10^{-14} \text{C/s} \quad (4-14)
\]

Therefore, the dose calculated from the measured current was found to be:

\[
D_{det} = \frac{Q_{prim}}{dm} \left( \frac{W}{e} \right) = \frac{(1.81 \pm 0.71) \times 10^{-14} \text{C/s}}{0.153 \times 10^{-3} \text{kg}} \cdot 27.5 \text{J/C} = (3.26 \pm 1.28) \times 10^{-9} \text{J/kg} \quad (4-15)
\]

Because the unit of dose \( \text{Gy} = \text{J/kg} \), the dose rate absorbed in the detector according to the measured current was \((3.26 \pm 1.28) \times 10^{-9} \text{Gy per second}\).

**Dose from spectrum**

In Section 4.3, the spectrum of Fe-55 was done using a Multichannel analyzer (Fig. 4-16). Because a spectrum is a measure of the number of times an incident particle had a specific energy, the integral of a spectrum gives the total energy absorbed by the detector. When calibrated into energy, the size of each channel (or bin) in the spectrum was 2.63 eV. Therefore, the integral of the spectrum taken at the same conditions as the energy calibration was calculated by multiplying the number of counts of each channel by 2.63 eV, and adding them all together. This gave \(1.64 \times 10^9 \text{eV}\). For this total energy, the dose is:

\[
D_{det} = \frac{dE}{dm} = \frac{1.64 \times 10^9 \text{eV}}{0.153 \times 10^{-3} \text{kg}} = 1.07 \times 10^{13} \text{eV/kg} = 1.71 \times 10^{-6} \text{J/kg} \quad (4-16)
\]

Because the Fe-55 spectrum was taken during a five minute period, this dose is the dose absorbed in five minutes. For comparison with the dose rate from current calculated before, it was converted into dose per second. The result was a dose rate absorbed in the detector of \(5.72 \times 10^{-9} \text{Gy per second}\). This value is about 1.8 times greater than the previous value.
Dose from oscilloscope signal

The dose imparted to the detector can be calculated from the signals on the oscilloscope. The signal is a graph of time versus voltage. Therefore, if it is divided by the input impedance of the oscilloscope, a time versus current graph is obtained. Integrating this graph will give a total charge. Just like with the current method of calculating dose, the total charge needs to be multiplied by four because there are four strips outputs, then divided by the gain at the voltage used (-4200V, $2.5 \times 10^6$) to get only the charge produced by primary gas ionizations. The result was $Q_{\text{prim}} = 1.94 \times 10^{-16}$C. Then the same dose equation was used with this charge:

$$D = \frac{Q_{\text{prim}}}{d} \left( \frac{W}{e} \right) = \frac{1.94 \times 10^{-16} \text{ C}}{0.153 \times 10^{-3} \text{ kg}} \cdot 27.5 \text{ J/C} = 3.49 \times 10^{-11} \text{ Gy}$$  \hspace{1cm} (4-17)

However, since this dose came from a single signal, it is the dose per pulse. To get the dose rate, it was multiplied by the activity $f$ of the Fe-55 measured under those same conditions on the same day, which was 166 pulses per second:

$$D_{\text{det}} = D_{\text{per pulse}} \times f = 3.49 \times 10^{-11} \text{ Gy} \cdot 166 \text{ s}^{-1} = 5.80 \times 10^{-9} \text{ Gy/s}$$  \hspace{1cm} (4-18)

The dose rate absorbed in the detector according to the oscilloscope signal method is therefore $5.80 \times 10^{-9}$ Gy/s, which is 1.8 times greater than the current method and 1.01 times greater than the spectrum method.

Dose from measured activity

Another more “theoretical” way to calculate the total energy absorbed by the triple-GEM detector is to multiply the number of counts measured with the detector by the theoretical average energy imparted into it per incident particle. In Section 4.5, the measured activity $f$ of the Fe-55 source was found to be $262 \pm 16$ CPS, and the average energy absorbed by the detector for each incoming particle is 5.9 keV (see Sec. 4.6). Using these values, the dose is:

$$D_{\text{det}} = \frac{dE}{dm} = \frac{E_{\text{Fe-55}} \cdot f}{dm} = \frac{5.9 \text{ keV} \cdot (262 \pm 16) \text{ CPS}}{0.153 \times 10^{-3} \text{ kg}} = 1.01 \times 10^{10} \text{ eV/kg} = (1.62 \pm 0.99) \times 10^{-9} \text{ Gy/s}$$  \hspace{1cm} (4-19)
This dose rate absorbed in the detector of \((1.62 \pm 0.99) \times 10^{-9}\) Gy per second is 2 times smaller than the calculation using the measured current, 3.5 times smaller than the dose calculation with the spectrum, and 3.6 times smaller than the calculation with the oscilloscope signal. It is hard to say which method is the most accurate, because the four have the same order of magnitude and close values. There are possible efficiency and temporal resolution errors with all of them, so it is an overall good result that they were this close. This also means that all methods can be used and calibrated to obtain the correct absorbed dose in the detector using radioactive sources.

4.8.2. Measuring dose from other radioactive sources

Since the four methods tested with the Fe-55 radioactive source for dose measurements were validated, any of them can actually be used. The best method to use in a clinical setting is the current method, since it is more common to have an ammeter in a hospital than an oscilloscope or a multichannel analyzer to form spectra. These two last options work best in laboratories and research institutions. Therefore, the dose rates absorbed in the triple-GEM detector from the other three radioactive sources available at the university (Sr-90, Tl-204, and Am-241) were calculated by measuring the current produced by each. The currents were measured at a supply voltage of 4200V and a gas flow of 0.3 l/min, from the left and right strips outputs connected in parallel. A total of 200 measurements were made for each source. The average current was then inserted into the following equation:

\[
D_{\text{det}} = \frac{Q_{\text{prim}}}{dm} \left( \frac{W}{e} \right) = \frac{1}{dm} \frac{Q_{\text{total}}}{G} \left( \frac{W}{e} \right) \tag{4-20}
\]

**Sr-90**

\[
D_{\text{det}} = \frac{1}{0.153 \times 10^{-3} \text{ kg}} \frac{4 \cdot 7.89 \times 10^{-9} \text{ C/s}}{2.5 \times 10^6} \cdot 27.5 \text{ J/C} = 2.27 \times 10^{-9} \text{ Gy/s} \tag{4-21}
\]

**Tl-204**

\[
D_{\text{det}} = \frac{1}{0.153 \times 10^{-3} \text{ kg}} \frac{4 \cdot 1.48 \times 10^{-9} \text{ C/s}}{2.5 \times 10^6} \cdot 27.5 \text{ J/C} = 4.25 \times 10^{-10} \text{ Gy/s} \tag{4-22}
\]
4.8 Dosimetry

Am-241

\[ D_{\text{det}} = \frac{1}{0.153 \times 10^{-3} \text{ kg}} \cdot \frac{4 \cdot 2.09 \times 10^{-9} \text{ C/s}}{2.5 \times 10^6} \cdot 27.5 \text{ J/C} = 6.01 \times 10^{-10} \text{ Gy/s} \] (4-23)

As can be seen, the radioactive source that deposited the most energy into the triple-GEM detector was Fe-55, followed by Sr-90, then Am-241, and lastly Tl-204. Of course these values depend on the efficiency of the detector, its sensitivity, and the interaction that each type of radiation has with the atoms of the gas. These all affect the amount of energy that the detector absorbs for each incident photon, which in turn changes the dose.

4.8.3. Measuring dose from the portable X-ray machine

![Figure 4-29: Schematic diagram of the experimental setup used to obtain the dose absorbed by the triple-GEM detector when irradiated by a portable X-ray machine.](image)

Even though it could have been more reliable to take data on the amplitudes of the signals and make a detailed statistical analysis on a computer, the required preAmplifier failed continuously, getting saturated with charge at even the lowest supply voltages and X-ray parameters. Therefore, the results with the multichannel analyzer and the preAmplifier became unreliable, so it was determined that the most accurate results were those obtained by analyzing the pulses on the oscilloscope.

Reference dose measurements were taken with a trustworthy dosimeter in order to check that the portable X-ray machine was behaving as expected, and to have data to compare the X-ray dose measurements taken with the triple-GEM detector afterwards. This reference data was obtained with the Victoreen RAD-CHECK ionization chamber by
taking exposure measurements in units of $R = cGy$ during one minute each. Within that minute an X-ray shot was fired at varying peak tube voltages and tube currents. The total dose without the X-ray shot, 0.008R, was taken as the background and subtracted from all measurements. Then, the values were corrected using the Victoreen detector’s calibration factor $N_K = 0.921$ and the temperature and pressure correction factor, $K_{TP} = 1.33$. To calculate it, the following equation was used:

$$K_{TP} = \frac{(273.2 + T) \, P_0}{(273.2 + T_0) \, P} \quad (4-24)$$

where $T_0 = 20^\circC$ and $P_0 = 101.325$ kPa are the reference conditions, and $T = 20^\circC$ and $P = 75.2$ kPa were the conditions on the day the measurements were made. The resultant graphs are shown in Figures 4-30 and 4-31.

**Figure 4-30:** Dose measured using the RAD-CHECK dosimeter vs Peak tube voltage, at an SOD of 90cm and a tube current of 16mAs. It was made to have an experimental reference of the relationship between the peak tube voltage and the measured dose from X-rays. It was fitted to a quadratic function because that is the theoretical relationship between peak tube voltage and dose, and gave an $R^2$ value of 0.9999.
Figure 4-31: Dose measured using the RAD-CHECK dosimeter vs Tube current, at an SOD of 90cm and a peak tube voltage of 73kVp. It was made to have an experimental reference of the relationship between the tube current and the measured dose from X-rays. It was fitted to a linear function because that is the theoretical relationship between tube current and dose, and gave an $R^2$ value of 0.99998.

The peak tube voltage vs dose graph was fitted to a quadratic function, because, even though both the maximum energy of the photons and the photon fluence increase in different ways with the tube voltage, “the relative area under each spectrum roughly follows a squared dependence” [18]. Instead, the tube current vs dose graph was fitted to a linear function because the photon fluence is directly proportional to the tube current (see Fig. 4-32). The fluence, of course, is also proportional to the absorbed dose. It is evident that both graphs made with the RAD-CHECK ionization chamber follow the theoretical relationships, as both have an $R^2$ value greater than 0.9999. Since these relationships were tested and gave the expected result, the triple-GEM detector was then tested as a dosimeter.

In order to measure the dose absorbed by the triple-GEM detector from X-rays at
different tube currents and peak tube voltages, the Siemens portable X-ray machine was used. Out of the four dose-measuring methods tested with the Fe-55 radioactive source (Sec. 4.8.1), only the oscilloscope signal method proved to be reliable. The current method is not ideal because the picoammeter does not have enough temporal resolution to measure the current precisely when the X-ray is fired, so lots of information is lost during its response and dead time (its maximum temporal resolution is 0.17ms and the X-rays require at least 10ms). The spectrum method is also not very useful because of the low temporal resolution of the preamplifier (100µs) and average energy resolution of the triple-GEM detector (19.5%), causing the small and thin signal that comes from the X-rays to be concealed by cosmic rays. Additionally, the amplification that allows for the calibration of the spectrum from channels to energy using the Fe-55 source is too much for the X-rays, so saturation occurs. This means that even if the X-ray spectra appeared correctly, it wouldn’t have been possible to connect channels to energy. Finally, the activity method is not ideal because counting the number of photons in an X-ray shot takes an extremely high temporal resolution (because there are around $10^8 - 10^{11}$ photons in a single shot), which most devices do not have. The oscilloscope, for example, gives a count of one for the whole shot. Since the oscilloscope signal method did demonstrate reliability, that was the

Figure 4-32: Change in X-ray spectra as a function of peak tube voltage (left) and tube current (right). The relative area under an X-ray spectrum has a squared relationship with peak tube voltage, while it is directly proportional to the tube current [18].
4.8 Dosimetry

one used.

Just like it was done for the Fe-55 source (see Sec. 4.8.1), the dose absorbed by the detector from X-rays was calculated using the signal on the oscilloscope. This was done by dividing every value into the input resistance (50Ω), integrating this time versus current signal, multiplying by the number of strips outputs (four), and dividing by the gain at the supply voltage used to get the charge produced by primary ionizations (2.5×10^6 at -4200V). Therefore, the dose was calculated from the total charge \( Q_{total} \) like this:

\[
D_{\text{det}} = \frac{1}{dm} \frac{4 \cdot Q_{total}}{G} \left( \frac{W}{e} \right) = \frac{1}{0.153 \times 10^{-3} \text{ kg}} \cdot \frac{4 \cdot Q_{total}}{2.5 \times 10^6} \cdot 27.5 \text{ J/kg} \quad (4-25)
\]

To minimize the chances of making mistakes with this calculation, a python code was written and tested who’s input is the data file that comes right from the oscilloscope, and who’s output is the dose absorbed in the detector.

The Siemens portable X-ray machine can be set at peak tube voltages from 40 – 125 kVp, and tube currents from 0.32 – 50 mAs (the range of the latter depends on the former). Therefore, data was taken varying both. A tube current of 16mAs, a peak tube voltage of 73kVp, and a distance from source to detector (SOD) of 88cm were chosen as the parameters that remained constant while the other was being varied. These values were picked because they are the average values of the parameters used in radiology.

The doses absorbed in the detector were then converted from dose absorbed in the detector into dose absorbed in air by using the procedure explained in the following section (Sec. 4.8.4), so that they could be compared to reference dose measurements taken with the RAD-CHECK ionization chamber. The resultant graphs are shown in Figures 4-33, 4-34, and 4-35.

As can be seen in Figure 4-33, the relationship between the voltage applied to the detector and the measured dose from X-rays is very close to exponentially decreasing, even though at higher voltages the efficiency of the detector is greater. This occurred because the current measured increased linearly, but the gain increases exponentially with applied voltage. Therefore, if the detector is to be calibrated with a reference dosimeter, it needs to be calibrated for that specific supply voltage. A voltage around -4200V was picked for the other tests because the detector has a high efficiency there, and the sort of plateau at the tail ensures that small variations in supply voltage do not affect the dose measured too.
Figure 4-33: Dose in air measured with the triple-GEM detector vs Supply voltage, with the X-ray machine set to a tube current of 64mAs, a peak tube voltage of 46kVp, and an SOD of 83cm. It was taken from the strips output, at a gas flow of 0.3 l/min with no amplification, and varying the supply voltage. It was made to study the relationship between the voltage applied to the detector and the measured dose from X-rays, and to determine the best voltage at which to measure dose. The relationship is very close to exponentially decreasing, showing that if the detector is to be calibrated with a reference dosimeter, it needs to be calibrated at a specific supply voltage. A voltage around -4200V is optimal because the detector is working at a high efficiency, and the sort of plateau at the tail ensures that small variations in supply voltage do not affect the dose measured too much.

At this supply voltage picked, dose measurements were taken for varying tube currents and peak tube voltages, and dose in air was graphed with each. The error bars correspond to the standard deviation of ten dose measurements taken at the same parameters. The relationship obtained with the triple-GEM detector for peak tube voltage versus dose in
air is clearly quadratic, although the high variance at low kVps makes the $R^2$ value of the quadratic fit be 0.95. And the relationship for tube current and dose in air is linear as expected, with an $R^2$ value of 0.97.

**Figure 4-34:** Dose in air measured with the triple-GEM detector vs Peak tube voltage, at an SOD of 88cm, a tube current of 16kVp, a supply voltage of -4200V, and a gas flow of 0.3 l/min. It was taken from the strips output, with no amplification, and varying the peak tube voltage. It was made to study the relationship between the peak tube voltage and the measured dose from X-rays. The relationship is clearly quadratic, although the high variance at low kVps makes the $R^2$ value of the quadratic fit be 0.95. The error bars correspond to the standard deviation of ten dose measurements taken at the same parameters.

Comparing Figures 4-34 and 4-35 to Figures 4-30 and 4-31 demonstrates that the triple-GEM detector is in fact able to measure dose from X-rays and obtain the expected relationships with peak tube voltage and with tube current, even though the variance is clearly greater for the triple-GEM detector than for the RAD-CHECK ionization chamber. However, the data from the triple-GEM detector is four orders of magnitude smaller than
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Figure 4-35: Dose in air measured with the triple-GEM detector vs Tube current, at an SOD of 88cm, a peak tube voltage of 73kVp, a supply voltage of -4200V, and a gas flow of 0.3 l/min. It was taken from the strips output, with no amplification, and varying the tube current. It was made to study the relationship between the tube current and the measured dose from X-rays. The relationship is linear as expected with an $R^2$ value of 0.97. The error bars correspond to the standard deviation of ten dose measurements taken at the same parameters.

The data from the RAD-CHECK detector. This is due to the fact that the RAD-CHECK detector has its maximum efficiency with X-rays, and was made for that specific purpose, while the triple-GEM detector experiences higher efficiencies with cosmic rays and radioactive sources, and was designed for detecting muons in high energy physics experiments.

The calibration function was found by graphing all of the values taken with each of the detectors at the same parameters, and comparing. As expected, the relationship between the reference doses and the doses measured on the triple-GEM detector is linear, which means that, if the $y$-intercept is close to zero, only a single calibration coefficient is needed in order to correct the triple-GEM measurement. A linear fit was done on the graph on
Fig. 4-36 that provides the required calibration function. This function was found to be
\[ \text{Dose} = 1.13 \times 10^4 \cdot \text{Measured Dose} - 1.71 \times 10^{-4}. \]
Because the \( y \)-intercept is so small, it can be said that the calibration coefficient for the triple-GEM detector’s dose measurement is \( 1.13 \times 10^4 \). It is evident that there is a relatively big variance in the data, yet this linear relationship proves that the triple-GEM detector is useful for measuring dose. With future adaptations and tests it has the potential of becoming a very accurate dosimeter.

There are various possible reasons why the calibration coefficient is so big. First, the efficiency of the triple-GEM, as shown in Section 4.5, is not too good for sources of energies as low as some keVs. For the Fe-55 source, for example, the dose would already have to be multiplied by around 550 to correct for the low efficiency. Additionally, because the oscilloscope was used to make these dose measurements, the energy resolution of the detector needs to be taken into account. At a 20\% energy resolution, it is expected that some information on the X-ray pulse is lost. The temporal resolution also plays its part, since there can be around \( 10^{10} \) photons in a single X-ray shot, and the oscilloscope is taking data sometimes for as long as a whole second. It does not have time to process every photon, so some information will be lost. With all this taken into account, it is expected that a calibration factor so big is necessary. This is no problem, anyway, because the correct relationships were obtained on all tests. This means that the triple-GEM detector has the capacity of measuring absorbed dose. Maybe a different dose-measuring method that was not studied here has less variance and gives better results, but the importance of this study is that it was proven that the triple-GEM detector has all the potential to become a commercial dosimeter one day.
Figure 4-36: Reference dose in air (measured with the RAD-CHECK ionization chamber) compared to Dose in air as measured with the triple-GEM detector. The linear fit provides the calibration function that allows the user to correct the dose measurement done with the triple-GEM detector. This function was found to be Dose = $1.13 \times 10^4 \cdot \text{Measured Dose} - 1.71 \times 10^{-4}$. Because the $y$-intercept is so small, it is also convenient to state that the calibration coefficient for the triple-GEM detector’s dose measurement is about $1.13 \times 10^4$. Even though there is a relatively big variance in the data, this linear relationship proves that the triple-GEM detector is useful for measuring dose, and with future adaptations it has the potential of becoming a very accurate dosimeter. The vertical error bars are too small to be visible in the graph because of the high precision of the RAD-CHECK detector.

4.8.4. Conversion from dose in detector to dose in air

In order to compare the doses given in the previous sections to the doses measured using other detectors, these doses had to be converted from dose in the detector to dose in air. This was done using Big Cavity Theory, which states that (see Sec. 2.7.3):
\[
\frac{D_{\text{med}}}{D_{\text{det}}} = \frac{K_{\text{col,med}}}{K_{\text{col,det}}} = \frac{\left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{med}}}{\left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{det}}} 
\]

\[
D_{\text{med}} = \left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{med}} \times D_{\text{det}} 
\]

where \(\left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{med}}\) and \(\left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{det}}\) are the mass energy absorption coefficients of the medium and of the detector respectively. These coefficients can be obtained from the NIST tables. Each element, compound, or mixture has its own coefficients, which depend on the average energy of the incoming photons. Because not all photon energies appear in the tables, a regression was done around the photon energies needed, and the resulting equation was used to approximate the coefficients. The mass attenuation coefficient \(\mu/\rho\) and the mass energy absorption coefficient \(\mu_{\text{en}}/\rho\) for air, for example, are graphed in Figure 4-37 for different average photon energies. The mass energy absorption coefficients for other materials, such as the ones that make up the human body, can be used to determine the absorbed dose while undergoing radiotherapy or getting an X-ray.

![Figure 4-37: Mass attenuation coefficients \(\mu/\rho\) and Mass energy absorption coefficients \(\mu_{\text{en}}/\rho\) for air vs Average photon energy. Data from NIST.](image-url)
When X-rays are used at different peak tube voltages, the average energy of the photons changes, so the mass energy absorption coefficients do too. But the dose can still be converted from one medium to the other using Big Cavity Theory as long as the correct coefficients are found.

Radioactive sources have the benefit that they have just one characteristic energy at which the coefficients need to be found. For the average energy of the Fe-55 source photons, 5.9 keV, the following values for the mass energy absorption coefficients in different relevant materials are:

- Dry air: \( \mu_{\text{en}}/\rho = 24.0 \text{ cm}^2/\text{g} \)
- Soft tissue: \( \mu_{\text{en}}/\rho = 25.3 \text{ cm}^2/\text{g} \)
- Adipose tissue: \( \mu_{\text{en}}/\rho = 15.3 \text{ cm}^2/\text{g} \)
- Cortical bone: \( \mu_{\text{en}}/\rho = 115 \text{ cm}^2/\text{g} \)
- Brain: \( \mu_{\text{en}}/\rho = 25.4 \text{ cm}^2/\text{g} \)
- Breast tissue: \( \mu_{\text{en}}/\rho = 20.3 \text{ cm}^2/\text{g} \)
- Lung tissue: \( \mu_{\text{en}}/\rho = 25.7 \text{ cm}^2/\text{g} \)
- Skeletal muscle: \( \mu_{\text{en}}/\rho = 25.1 \text{ cm}^2/\text{g} \)

The mass energy absorption coefficient for 5.9 keV photons in the triple-GEM detector was calculated doing a weighted average of the coefficients for argon, carbon, and oxygen, the components of the gas mix \([56]\):

\[
(\mu_{\text{en}}/\rho)_{\text{det}} = 0.75 \cdot (\mu_{\text{en}}/\rho)_{\text{Ar}} + 0.08 \cdot (\mu_{\text{en}}/\rho)_{\text{C}} + 0.17 \cdot (\mu_{\text{en}}/\rho)_{\text{O}} = 186 \text{ cm}^2/\text{g} \quad (4-28)
\]

Therefore, the following equation can be used to calculate the dose in each medium for the Fe-55 radioactive source:

\[
D_{\text{med}} = \frac{(\mu_{\text{en}}/\rho)_{\text{med}}}{186 \text{ cm}^2/\text{g}} \times D_{\text{det}} \quad (4-29)
\]
The dose rate deposited by the Fe-55 source in air, for example, according to the average of the four calculations (Sec. 4.8.1), would be:

\[
D_{\text{air}} = \frac{24.0 \text{ cm}^2/\text{g}}{186 \text{ cm}^2/\text{g}} \cdot 4.10 \times 10^{-9} = 5.29 \times 10^{-10} \text{ Gy per second} \quad (4-30)
\]

The reference value for this dose in air was measured with the Inspector detector, which gives the exposure rate in mR/hr. The variance is very big, but the measured value was 27 ± 4 mR/hr. One röntgen deposits 0.00877 grays of absorbed dose in dry air, so the dose deposited by the Fe-55 source was \((6.6 \pm 1) \times 10^{-8}\) Gy/s according to the Inspector detector. This is 124 times greater than the dose in air according to the triple-GEM detector, meaning that if the triple-GEM were to be calibrated with the Inspector, the calibration coefficient would be 124. However, the Inspector detector is not the best reference for an Fe-55 source, since it was calibrated with a Cs-137 source of 512keV betas and in general is meant to measure radioactivity of much higher energies. In fact, in table 4-4 the efficiency of the Inspector detector was found to be 1.1% with the Fe-55 source. This means that the real dose imparted to the air by the source must be about 91 times higher than that measured on the Inspector detector. If this is taken into account, the calibration coefficient for measuring dose in air with the triple-GEM detector would be \(1.13 \times 10^4\). This is exactly the same calibration coefficient found for the X-ray dose measurements. The fact that this result is the same for two different radiation sources is very promising, and means that no matter the type or energy of the incident radiation, the absorbed dose can be found from the one measured on the triple-GEM detector by multiplying it by \(1.13 \times 10^4\).

### 4.8.5. Viability of dosimetry applications

As previously said, the triple-GEM detector proved to be suitable for dose measurements, since a proportionality constant was found that calibrates it to get the correct dose measurement, for either an Fe-55 radioactive source or an X-ray shot at a wide range of a tube current and peak tube voltage values. This calibration factor was constant regardless of energy, type of radiation, or detection sensitivity or efficiency. Most dosimeters that work with X-rays do not work with radioactive sources, and vice versa. Likewise, most dosimeters that work with high energy radiation do not work with low energy radiation, and vice versa. So having demonstrated that the triple-GEM detector measures dose equally
well for all the radiation sources and energies tested is quite promising.

Because triple-GEM detectors have countless advantages such as flexible geometries, large detection areas, pixel readout panels, low noise, the possibility of mass production, and are relatively inexpensive, using them as dosimeters has become an intriguing proposal. Proving that they do work for this purpose is a very meaningful result.

In terms of specific applications, the two most tested sources of radiation were radioactive sources and X-rays at the energy range used in radiology. Radioactive sources had the advantage that more methods were available for measuring dose, and all worked equally well. Some of those, such as the current method and the activity method (see Sec. 4.8.1), have a greater chance of being used at a medical setting, since ammeters and counters are commonly available in hospitals. Therefore, it seems reasonable that the triple-GEM detector could become a very useful and advantageous dosimeter in nuclear medicine. Additionally, triple-GEM detectors have the possibility of using a pixelated readout board with really good spatial resolution, which would allow users to make maps of the location where dose is being received and in what quantity. None of the current dosimeters do this, and it could result essential for the exact calibration of various sources of radiation. This in turn could help reduce the unwanted dose that patients receive in treatments because of non-uniform radiation.

Even though the triple-GEM detector responded equally well with X-rays as with radioactive sources, the only reliable dose-measuring method for X-rays was the oscilloscope method. It is less likely for an oscilloscope to be available at a medical setting, because it is mostly used for research in the academic field. However, other methods that were not studied in this project could be discovered, which would open the door to measuring dose coming from X-rays of radiology and radiotherapy energies in hospitals. For example, getting an ammeter with a very high temporal resolution may be all that is needed for the current method to work correctly with these X-rays.

Since the triple-GEM detector was proven to work as a dosimeter, more studies on this topic are justified. There is a lot to gain from its countless benefits and not much to lose. The only thing that had to be determined was if its proportionality to energy could be exploited for dose measurements, and fortunately it can. Therefore, more than having to adapt the detector to dosimetry, more appropriate electronics and devices could be used.
5 Conclusions and future work

Once the triple-GEM detector of CRYOMAG research group at Universidad Nacional de Colombia was left up and running after initial fixes, the optimal functioning parameters were found to be: a supply voltage of -4325V, a threshold of 1.3mV, and a gas flow of 0.3 l/min for cosmic muons, and a supply voltage of -4200V, a threshold of 2.0mV, and a gas flow of 0.3 l/min for an Fe-55 radioactive source.

The characteristic properties of the triple-GEM detector were measured, and the following results were obtained: an energy resolution of 19.5 %, a temporal resolution of at least 40ns, a maximum gain of $(4.7 \pm 1.3) \times 10^6$, and a greater sensitivity to cosmic muons than to any of the radioactive sources tested.

Doses were measured with radioactive sources and with a portable X-ray machine. For both, a calibration coefficient of $1.13 \times 10^4$ was obtained against the respective reference values of each source of radiation. The viability of the triple-GEM detector as a dosimeter was studied and it was found to be a very promising and useful tool for measuring dose, especially in nuclear medicine applications.

Advantages of the triple-GEM detector such as reaching high amplification factors at relatively low voltages, maintaining energy proportionality throughout its functioning range, low noise, a fast electronic signal, and ease of manipulation were demonstrated while doing this project.

Finally, the objectives of the project were met: the typical signals for cosmic muons, a Fe-55 radioactive source, and X-rays were characterized in terms of amplitude, duration, and shape; the gain, efficiency, sensitivity, and energy resolution of the triple-GEM detector were measured; the Fe-55 spectrum was obtained and used to calibrate channels with respect to energy; and the detector’s behavior as a dosimeter was tested and analyzed.

Yet there are still things that can be done in the future, that go beyond the scope of this project. Now that it was proven that the triple-GEM detector works satisfactorily
in measuring doses, its behavior could be studied with different gas mixes that are more practical and common in clinical settings, such as purified air. Even though this wanted to be done, the gases available at the laboratory were not pure enough, and it was decided that for the safety of the detector they would not be used. New gas tanks take too long to arrive, so other tests were prioritized. The reliability of some of the obtained results could be improved by using different methods that were impossible to use in this project, such as using a telescopic arrangement of scintillators and photomultipliers to measure cosmic muon efficiency, using a counter to measure the activity of radioactive sources, and using a preAmplifier together with a Multi-Channel Analyzer to study the amplitude (and charge) of signals statistically.

Additionally, it could be very valuable to test the response of the triple-GEM detector as a dosimeter with radioactive sources of higher energies, such as the ones used in nuclear medicine, radiotherapy, and brachytherapy. Because of how well it worked with X-rays and radioactive sources at a wide range of energies, it is very possible that the detector will keep working correctly at even higher energies. If this is the case, more applications could be discovered. All in all, this project achieved what it set out to do: prove that the triple-GEM detector not only works very well for the high energy physics applications for which it was designed, but also for countless other applications, and particularly for medical physics.
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