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**The Gas Electron Multiplier (GEM):
A New Detector for Scanned Projection
Radiography**

by

Mei Li

B. Sc. (Shandong University, 1991)

M. Eng. (China Institute of Atomic Energy, 1998)

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of

Master of Science

Ottawa-Carleton Institute for Physics

Department of Physics

Carleton University

Ottawa, Ontario

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The undersigned hereby recommended to
the Faculty of Graduate Studies and Research
acceptance of the thesis

**The Gas Electron Multiplier (GEM): A New Detector for Scanned
Projection Radiography**

Submitted by

Mei Li, B.Sc., M.Eng.

In partial fulfillment of the requirements
For the degree of Master of Science

Chair, Department of Physics

Thesis Supervisor

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date 14th Sept 2000

Carleton University

Abstract

A prototype scanned projection radiography (SPR) system has been constructed using a high-pressure photon counting detector filled with a Xe:CH₄ gas mixture. The detector combines a Gas Electron Multiplier (GEM) and a Gas Microstrip Detector (GMD). The energy deposited by each incident photon can be measured when photon counting is done. A GMD imager using Xe:CH₄ was previously built in our lab, and showed very promising spatial resolution and energy resolution. In order to improve the electrical stability of the GMD imager, the GEM is coupled to the GMD as a pre-amplification element. The GEM is basically a foil perforated by many high precision holes. Electron amplification happens at the centers of these holes. With the gain contribution from the GEM, the GMD gain and operating voltage can be decreased, thereby improving its reliability.

The stable operation of the GEM/GMD hybrid detector from 1-4 atm has been demonstrated. The cathode voltage on the GMD is significantly lower than that which was applied in the GMD imager at a given gas gain. The modulation transfer function was measured at 1-4 atm for 10-50 kV x rays. Compared with the GMD imager, the limiting resolution at 4 atm increases from 14.0 to 17.8 lp mm⁻¹ for 13 kV, increases from 6.2 to 7.0 lp mm⁻¹ for 30 kV, and increases from 7.0 to 11.9 lp mm⁻¹ for 50 kV. At 4 atm, the energy resolution is 10% for 17.7 keV and 7.9% for 59.6 keV. The system is more robust than the GMD imager without degradation of the spatial resolution.

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List of Abbreviations

ADC	analog-to-digital converter
CCD	charge coupled device
CERN	European Organization for Nuclear Research
DQE	detective quantum efficiency
ESF	Edge Spread Function
FFT	Fast Fourier Transform
FOV	field of view
FWHM	full-width half maximum
GEM	gas electron multiplier
GMD	gas microstrip detector
LBNL	Lawrence Berkeley National Laboratory
lp mm ⁻¹	line pairs per millimeter
LSF	line spread function
MCA	multi-channel analyzer
MDC	Micro-Dot avalanche Chamber
MSGC	MicroStrip Gas Chamber
MIC	Multistrip Ionization Chamber
MICROMEGAS	MICRO-MEsh Gaseous Structure
MTF	modulation transfer function
MWPC	MultiWire Proportional Chamber
Opamp	operational amplifier
PCB	printed circuit board
PMMA	polymethyl methacrylate
SDRD	Siberian Digital Radiographic Device
SNR	signal to noise ratio
SPR	scanned projection radiography
TFT	thin-film transistor

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Chapter 1

Introduction

Since the discovery of x rays in 1895 by Wilhelm C. Roentgen, the realm of diagnostic medical imaging has witnessed continual dramatic changes in the capabilities and extent of visualizing the human body. This chapter reviews the conventional x-ray imaging technology and the recent advances in digital radiography. The previous work, the Gas Microstrip Detector (GMD) imager, is described. An overview is given of the thesis.

1.1 Conventional X-ray Imaging

Conventional x-ray imaging uses photographic film in combination with a fluorescent screen as the imaging receptor [1]. In response to x-ray absorption, the phosphor screen emits light by which the film is exposed to form a latent image. This image is rendered visible through chemical processing of the film, and the image is usually viewed with the aid of a view box or illuminator [2].

The film operates on the principle of energy integration, i.e. the value of each pixel is a function of the energy deposited in the detector volume corresponding to that pixel. The primary disadvantage of screen/film radiography is that the image cannot be adjusted after it has been developed. Since the film is used as the x-ray detector, the image display and for the storage medium, there is a limitation on the image quality and dose efficiency.

1.2 Digital Radiography

The term “digital radiography” means that the analog data collected from the patient are converted into digital form so that the diagnostic information can be recorded, processed, displayed and stored by a digital computer [2]. The speed, accuracy, and versatility of the computer have greatly broadened the selection and presentation of information which are subsets of the primary images [3].

Digital radiography has many advantages over conventional radiography. The primary advantage is the level and window interactive display. The image contrast in numerous segments of one image can be expanded with selected base levels and window widths. Therefore the user can see details which otherwise would require several exposures, even for digitized film data. On the other hand, since digital images can be stored, sorted, retrieved, and duplicated with no degradation, it is easier to compare x-ray images with those obtained from other imaging modalities; permits image networking within the hospital for remote access and archiving; and permits teleradiology — wherein highly qualified personnel could service remote or poorly populated regions from a central facility [4].

Recent advances in digital electronics and manufacturing methods have led to many approaches for the design and construction of digital x-ray detectors. Little by little, the film-based x-ray imaging technology is gradually being replaced by digital radiography. Electronic x-ray detectors can be divided into two classes according to their working mode: energy integration mode and photon-counting mode.

1.2.1 Energy Integration Mode Detectors

For this type of detector, images are generated by integrating the total energy deposited in the detector during the whole radiation exposure. Most of the available large-area, electronically readable detectors currently on the market work in the energy integration mode, including photostimulable phosphors, Charge-Coupled Device (CCD) sensors coupled to conventional phosphors, and solid-state detectors made of semiconductor materials or photo-conductor materials such as silicon, amorphous selenium,

etc. These detectors can be classified into two categories: direct conversion and indirect conversion. Direct conversion means that the x rays deposit their energies in a layer of photoconductor and the charge signal is read out to form the image. In indirect conversion, a phosphor screen is used to absorb x rays and the consequent light photons are captured by a photo-detector to generate the image charge signal.

Recent advances in photolithography and electronic micro-fabrication techniques have enabled the development of large-area x-ray detectors with integrated readout mechanisms based on arrays of thin-film transistors (TFT) [5]. Unlike older, CCD-based detectors that require optical coupling and image demagnification, TFT based systems are constructed such that the pixel charge collection and readout electronics for each pixel are immediately adjacent to the site of the x-ray interactions.

TFT arrays are used as the active electronic switches in both indirect and direct conversion detectors [5]. These arrays are typically deposited onto a glass substrate in multiple layers. The readout electronics are at the bottom of the multiple layers. In the middle layers are the charge collector arrays, which include the pixel electrodes and the integrated storage capacitors that are connected with TFT switches. These TFT switches are controlled by a scanning control circuit by which the charge signals stored in the capacitors are read out row by row. Then, depending on the type of detector being constructed, x-ray elements, light-sensitive elements, or both, are deposited to form the top layer. The entire assembly is encased in a protective enclosure with external cabling for computer connection.

1.2.1.1 Direct Conversion Detectors

In a direct conversion detector, an x-ray photoconductor is used to convert x-ray photons into an electric charge directly. Typically, amorphous selenium is used as the photoconductor material because of its excellent x-ray detection properties [6, 7, 8] and extremely high intrinsic spatial resolution [9].

Solid-state detectors made of amorphous selenium layered on an aluminum support were introduced in the mid 1950's as xeroradiography that used the powder readout method. Attempts at using a sensitive electrostatic probe to extract the latent charge

distribution were not commercially successful until a charged selenium drum/electrostatic readout system for chest radiology was introduced in 1993 by Philips Medical Systems [10].

Amorphous selenium is well developed technologically as it has been used as a photoconductor in photocopiers for decades. It has two advantages as an x-ray imaging detector. First, as selenium is used in its amorphous form, selenium plates can be made by means of evaporation and thus can be made large in area relatively easily and inexpensively. Second, it has low dark current.

Solid-state semiconductor detectors with TFT arrays layered directly on the surface to collect the signal and read it out are currently in research and development for selenium and for silicon [4]. During x-ray exposure, energy is absorbed by the amorphous selenium layer and the charge created is drawn to the surfaces by the internal electric field. The image charge is collected by the pixel electrode and accumulated onto the pixel storage capacitor. The pixel electrode and storage capacitor are connected to the TFT switch of each pixel. During readout, the scanning control circuit generates pulses to turn on all the TFT switches on the first row of the array and transfers charge from the pixel capacitors to the readout rails (columns). The charge is then collected and amplified by an amplifier on each rail and the data for the entire row are multiplexed out. This sequence is repeated for each subsequent row until the entire array is readout.

Technology for solid-state detectors is advancing rapidly and will likely provide array sizes of $4,000 \times 4,000$ elements in the near future to match the capabilities of screen/film systems for both static and dynamic projection imaging [10].

1.2.1.2 Indirect Conversion Detectors

Indirect conversion detectors have a two-step process for x-ray detection: a phosphor screen is used to absorb the x rays and converts the x-ray energy into visible light. The light is then converted into an electric charge by CCDs, or by means of photo-detectors such as amorphous silicon photodiode arrays followed by a TFT array.

CCD sensors are typically comprised of an array of electron “wells” etched in silicon or germanium that collect electrons released via the photoelectric effect by

impinging light. Charge transfer of the stored electron charge occurs over vertical registers line by line; charge detection is accomplished by sequential readout of the horizontal register on a pixel-by-pixel basis with charge conversion to a voltage at various readout rates. Pixel location is accomplished using synchronization signals often identical to standard video format. Common array sizes for CCD cameras are $1,000 \times 1,000$ and smaller. CCD cameras are presently being used in digital photo spot applications with the image-intensifier television system that is used in fluoroscopy. Direct coupling of CCD array cameras to fiber optic plastic and glass scintillators will likely be available in the near future [10].

Another indirect detector is the photostimulable phosphor that is used in computed radiography [10]. In the early 1980's, Fuji Film Company of Japan introduced the photostimulable phosphor plate and plate readers. An "electron" latent image is formed when the phosphor electrons are excited by the radiation, then the latent image is developed in the reader by scanning the exposed plate with a focused laser beam of low energy to release those excited electrons back to ground state.

1.2.2 Photon-Counting Mode Detectors

Compared with energy integration, the photon-counting mode has several advantages. First, the detective quantum efficiency (DQE) (the definition of DQE is given in section 2.7) of a photon-counting system can be nearly equal to the quantum efficiency. So it does not introduce extra noise besides the statistical noise. Second, it can provide the energy of each photon that is stopped inside the detector and contributes to the images. Third, because each photon produces a signal on multiple detection elements, the centroid of the charge distribution can be calculated and the resolution can therefore be better than the element pitch.

Generally, photon counting is used in nuclear medicine where the photon fluence rate is low, but it is not used in radiography because of the technical difficulties involved in counting photons at radiographic fluence rates and of providing adequate spatial resolution. With the advent of new high resolution, high-rate radiation counters

developed for particle physics experiments, photon-counting radiography has become feasible.

The recently introduced micro-pattern detectors for particle physics, such as the Gas Microstrip Detector (GMD), Micro-Dot Avalanche Chamber (MDC), MICROMEGAS, and the Gas Electron Multiplier (GEM) etc., broaden the way for digital radiography photon-counting detector development.

Gas Microstrip Detector (GMD)

The GMD, invented in 1988 by Oed, was the first of the microstructure gas detectors [11]. Its anodes and cathodes are metal strips printed onto a flat glass substrate, as shown in Figure 1.1. With the help of high-accuracy photolithographic technology, the distance between anodes and cathodes is an order of magnitude smaller than that in the conventional multiwire proportional chamber (MWPC), which brings advantages in terms of rate capability and spatial resolution. High voltage is applied on the cathodes so that a high electric field is produced around the anodes and provides the proportional multiplication of the electrons. The GMD has been found to age and also subject to damage due to electrical discharges resulting in an unreliable operation, when it is exposed to high-rate radiation.

Gas Electron Multiplier (GEM)

The Gas Electron Multiplier (GEM) was introduced by F. Sauli in 1997 as a gain booster for the GMD [12]. It consists of a thin metal-clad polymer foil chemically perforated by a high density of holes. Figure 1.2 shows the geometry of one GEM channel. On application of a difference of potential across the GEM mesh, it acts as an amplifier for electrons released by radiation in the overlying gas volume. With the gain contributed from the GEM, the GMD can be operated at lower and safer voltage resulting in more reliable operation of the device.

Figure 1.1 Concept diagram of the GMD in the GMD imager.

Figure 1.2: Schematic of one GEM amplification channel (D: the copper diameter; d: the Kapton diameter; S: the thickness of the copper electrode; T: the thickness of the Kapton).

Micro-Dot Avalanche Chamber (MDC)

The Micro-Dot avalanche Chamber (MDC) was introduced by Biagi *et. al.* [13]. It is a 2-D gas detector. Figure 1.3 shows the geometry of one micro-dot cell. It is realized on a silicon substrate. The device consists of metallic anode dots surrounded by circular field and cathode rings acting as individual proportional counters. The structure has been implemented with an underlying backplane bus enabling the anode dots to be read out in strings which have been produced with both 100 and 200 μm readout pitch. The other dimension is provided by the cathodes which are connected together in lines too. The anode dots are typically 12 to 20 μm in diameter and the cathodes are between 20 and 40 μm wide. The anode cathode gap is of the order of 75 μm for a 200 μm pitch and 35 μm for a 100 μm pitch structure. Compared with the GEM, the fabrication is more complicated and expensive.

MICRO-MESh Gaseous Structure (MICROMEGAS)

MICROMEGAS was invented at Saclay by Y. Giomataris, Ph. Rebourgeard and J.P. Robert, in collaboration with G. Charpak [14, 15]. The geometry of the MICROMEGAS detector is shown in Figure 1.4. It consists of a conversion gap and a thin amplification gap. The two regions are separated by a thin (3 or 4 μm) grid which rests on small insulating pillars of 200 microns diameter. The incident radiations liberate ionization electrons in the conversion gap, and then these electrons drift into the amplification gap. A high field is applied across the amplification gap, typically above 60 kV/cm [16]. Here the electrons are amplified and finally collected by printed electrodes of any shape.

The major practical inconvenience is the necessity of stretching and maintaining parallel meshes with very good accuracy [17]. This requires a heavy support frame. The presence of strong electrostatic attraction forces makes the mesh sag, especially for large sizes. The introduction of the insulating pillars makes the assembly of a MICROMEGAS detector complicated.

Figure 1.3: Schematic of one micro-dot cell.

Figure 1.4: Schematic of the MICROMEAS detector.

1.3 Scanned Projection Radiography (SPR)

When only one dimension of the field of view (FOV) of a detector is as large as the image and the other dimension is much smaller, scanning is used to generate a two-dimensional image. In a scanned projection radiography system, the x rays are collimated into a fan-beam before and after the object to irradiate the FOV of the detector. The two dimensional image is generated by scanning the object with the fan-beam.

Compared with direct two-dimensional projection systems, e.g. CCDs or Selenium system, scanned projection radiography has two advantages if designed properly: it reduces scatter background and the number of readout channels. The reduction of the scattered photons results in better detection of low contrast lesions. The drawbacks of SPR are high x-ray tube heat loading because of poor x-ray utilization with a fan beam, and difficulty in implementing real time imaging (fluoroscopy) because the time required to produce one image is quite long.

A digital x-ray imaging system, the Siberian Digital Radiographic Device (SDRD), has been developed by a group from the Budker Institute of Nuclear Physics in Novosibirsk [18, 19] and is in clinical use at hospitals in Novosibirsk and Moscow. The SDRD is a slit scanned projection radiography system based on the multi-wire proportional chamber (MWPC). The MWPC works in photon-counting mode with the keystone geometry, i.e., the anode wires are stretched along the direction of the beam and directed to the source of radiation (focus of the x-ray tube) [20]. The advantages of the SDRD over film-screen have been demonstrated [21].

A new detector, the Multistrip Ionization Chamber (MIC), is being developed by the same group [22]. The signal electrode consists of 1024 strips with a pitch 0.4 mm, which are made by printed circuit technology. Each strip is about 60 mm long and is directed to the focal spot of the x-ray tube. There are 16 groups of 64 strips each. The gap between the drift plane and the readout electrode is 4 mm, and is filled with pure Xe at 10 atm. The detector operates in the ionization regime. It was demonstrated that the MIC has better spatial resolution, higher quantum efficiency and much simpler design compared with the MWPC.

1.4 Previous Work: Gas Microstrip Detector (GMD) Imager

A Gas Microstrip Detector Imager filled with high pressure Xe:CH₄ has been built in our lab. The slit-scan mode of scanned projection radiography (SPR) was used in the GMD imaging system. Good performance of the GMD imager was demonstrated [23].

The GMD used in the imager has 7 μm wide anodes, 90 μm wide cathodes, and a pitch of 200 μm . The orientation of the detector is shown in Figure 1.1. Any electrons liberated by the interaction of an x-ray photon with the xenon between the GMD and the drift plane 3.9 mm away are driven towards the anodes. The GMD mounting geometry, which was carried over from particle physics tracking applications, restricted the sensitive xenon thickness to 3.9 mm.

1.5 Motivation for This Project

A slow degradation of performance and a substantial increase with time of the discharges was observed during the operation of the GMD imager [24]. The discharge contributes to the spurious signal and damages the GMD anodes and cathodes which could result in dead channels after a period of operation.

Discharge formation

The formation of the discharges has been researched by many groups [25, 26, 27, 28]. Many parameters like the quality of GMD strips or the contaminants in the gas can provoke discharges. Besides, two physical processes have been proposed to be responsible for discharges, which would produce permanent damage to the GMD electrodes. One is field emission at the cathode strip edges, and the other is the formation of streamers [29]. Both of them are related with the Raether condition, i.e. the number of electrons in the avalanche reaches $10^7 \sim 10^8$.

First, consider the field emission. Due to the high field around the cathodes, one or more electrons are emitted at the cathode strip edges. This field emission would be enhanced by the presence of ions produced in avalanches around anodes. Once ejected,

the electrons are multiplied in the high field around the cathode edges before reaching the anode strips. This process can easily become divergent. Then the discharge happens when the avalanche size approaches the Raether condition.

An alternative mechanism involves the transition from avalanche to streamer at the Raether condition. When the total charge in the avalanche exceeds Raether's limit, the enhancement of the electric field in front of and behind the primary avalanche is such as to induce the fast growth of secondary avalanches, and the appearance of a long, filament-like forward and backward charge propagation named a streamer. In a uniform, strong electric field, the streamer propagates all the way through the gap. The outcome of the process is the creation of a densely ionized, low-resistivity channel between anode and cathode, inevitably leading to discharge [30].

Solution

A discharge initiated by any of the mechanisms can lead to a spark, which would damage the electrodes and further result in the failure of the detector. The GMD is rather delicate to use and prone to failures caused by discharges at the operating voltage required for full efficiency. Much research work has been done to look for solutions to this problem [26]. One of them would be coupling the recently introduced Gas Electron Multiplier (GEM) to the GMD.

The GEM is a new concept for electron amplification in gas detectors [12]. An interesting use of the GEM mesh is as gain booster for the GMD. It acts as a powerful preamplifier for electrons released in the conversion volume, thereby the "primary" charge is increased from the point of view of the second amplification stage [31]. In this way, the demand of a high GMD gain for an appropriate signal-to-noise ratio is relaxed, so that the detector can be operated at lower and safer anode-cathode voltages. Thus the whole system is more reliable and robust.

The purpose of our research work is to determine:

1. If the GEM/GMD hybrid is more robust;
2. If the addition of the GEM degrades the spatial resolution and energy resolution of the GMD;

3. If the GEM is suitable for high pressure digital radiography.

1.5 Thesis Overview

Chapter 2 introduces the GEM and its operating principles. The signal development in the GEM/GMD hybrid is described. Chapter 3 describes the geometry of our imaging system with the GEM/GMD hybrid detector. Some concepts used for the GEM are introduced. The apparatus and electronics used in the imaging system are described. Chapter 4 introduces the experimental methods used to measure the performance of our hybrid system. The experimental results are presented and compared with the performance of the GMD imager. Some images obtained from the hybrid system are shown. The conclusions from the measurement, and future work for this project are discussed in Chapter 5.

Chapter 2

Theory

The Gas Electron Multiplier (GEM) was introduced by F. Sauli in 1997 [12]. Its principal distinction from the MWPC and the GMD is that the gas amplification occurs in micro-holes [32]. This chapter introduces the geometry of the GEM and its manufacturing technology; the principle of the GEM operation, including the signal development in the GEM/GMD hybrid and the parameters affecting the gas gain of the GEM; the optimization of the GEM; and finally describes the spatial resolution and energy resolution in the GEM/GMD hybrid.

Figure 2.1: A close view of a GEM foil.

2.1 GEM Geometry

A GEM consists of a Kapton mesh typically 50 μm thick coated with 5 μm of copper on both sides of the Kapton, and perforated regularly by a high density matrix of

holes. The cross-section and top view of the GEM holes are shown in Figure 1.2. The approximate dimensions of a standard GEM are: Kapton thickness (T) 50 μm , copper thickness (S) about 5 μm , copper hole diameter (D) about 70 ~ 90 μm , Kapton hole diameter (d) about 50 ~ 60 μm , and the pitch 140 μm . A close view of the GEM foil is shown in Figure 2.1.

2.2 Operating Principle of the GEM

The GEM works in the proportional regime, which means that the amplitude of the output signal is proportional to the initial number of ion pairs produced by the incident photon.

In our hybrid GEM/GMD detector, the GEM is used as an avalanche preamplifier for the GMD. Figure 2.2 gives the orientation of the hybrid detector. The GEM is placed between the parallel drift plane and the GMD substrate. The gap between the drift plane and the GEM top is called the drift region or conversion gap, and the lower space, where amplified electrons are collected by the GMD anodes, is named the induction region or collection gap [33].

2.2.1 Electric Field in GEM holes

Upon application of a potential difference between the GEM electrodes (copper layers), a high electric field develops in the holes focusing the field lines between the drift electrode and the GMD anodes, thereby providing an effective amplification path for electrons released by ionization in the gas and drifting in the high field through the open channel.

The field density in the amplifying channel can be varied either by increasing the potential difference between the upper and the lower electrode of GEM, or by reducing the diameter of the GEM holes [41]. The length of the amplifying channel, for a single GEM grid, is fixed by the thickness of the insulating foil [34]. So far most GEM foils have an insulator thickness of 50 μm . So the electric field in the GEM hole is about 100 kV/cm when the potential difference across the GEM is 500 V.

Figure 2.2: The orientation of the GEM/GMD hybrid detector.

Along directions perpendicular to the axis of the holes, the field strength is almost uniform in the center and increases sharply near the sides, particularly close to the copper-Kapton interface. This determines how high a voltage could be applied to the GEM, i.e. the point of electrical breakdown [33]. The charge avalanche transverses the GEM hole mostly in the center, but a fraction of it could approach this extremely high field region on the sides of the hole due to diffusion and trigger a discharge. Also electron emission from the GEM electrodes in this area is possible [34].

2.2.2 Gas Avalanche

The mean free path for ionization is defined as the average distance an electron has to travel before it gets involved in an inelastic collision, where ionization occurs. The inverse of the mean free path for ionization is called the first Townsend coefficient, α , and is the number of ion pairs produced per unit length of drift [34].

Avalanche multiplication is based on a process of ionization by collision. Consider one free electron producing one more electron after a mean free path. Both continue along the drift field, and after one more mean free path, two further ion pairs are created, and so on. If N is the number of electrons at a given position, after a displacement dx , the increase in the number will be:

$$dN(x) = \alpha N(x) dx \quad . \quad (2-1)$$

By integrating Eq. (2-1):

$$N(x) = N_0 e^{\alpha x} \quad \text{or} \quad M = \frac{N(x)}{N_0} = e^{\alpha x} \quad . \quad (2-2)$$

This expression, where M is the gas gain, is deduced for the case of a uniform electric field. If the electric field is non-uniform, α depends on the distance x , so the gas gain is:

$$M = e^{n \int_{x_1}^{x_2} \alpha(x) dx} \quad (2-3)$$

The lower integration limit x_1 is the coordinate at which the charge multiplication starts due to high electric field, and x_2 is the coordinate where the multiplication process stops.

If a single primary electron enters a region of sufficiently high field, it will experience further ionizing collisions. The different drift velocities of electrons and ions (several thousand times slower) cause the avalanche to have a characteristic drop shape, with electrons situated in the front of the drop and the ions in the tail.

2.2.3 Signal Development in the GEM/GMD Hybrid

The interaction of photons with matter is described by four fundamental processes: the photoelectric effect, the Compton effect, coherent scattering and pair production. For the photon energies used in diagnostic radiology (15 ~ 150 keV), only two interactions are important, the photoelectric effect and Compton scattering. Coherent scattering is numerically unimportant, since it does not deposit energy in the detector. The probability of Compton scattering depends on the total number of electrons in the absorber, and it is more important for higher diagnostic energies [35]. The photoelectric effect is the predominant interaction with low energy photons and with high atomic number absorbers [36]. The law governing the photoelectric effect is [37]:

$$\frac{\tau}{\rho} \propto \frac{Z^n}{E_\gamma^m} \quad (2-4)$$

where $\frac{\tau}{\rho}$ (cm^2 / g) is the mass coefficient, τ (cm^{-1}) is the linear attenuation coefficient, ρ (g/cm^3) is the density of the absorber, Z the atomic number of the absorber, and E_γ the photon energy. The powers n and m are photon energy and Z dependent. For biological materials at all x-ray energies, or for high Z materials at photon energies lower than that 0.5 MeV, $n \approx 3$. For low Z materials, $m \approx 3.8$; and for high Z materials, $m \approx 3$. In our

case, the x-ray energy is lower than 50 keV and xenon gas ($Z = 54$) is used, so the photoelectric effect is the main mechanism.

As shown in Figure 2.2, x-ray photons are incident on the detector normally, i.e., the x-ray beam is perpendicular to the drift plane, and interact with gas atoms in the conversion gap. Any primary electrons liberated by the interaction of photons with the gas in the conversion gap experience two stages of amplification. The first stage is in the intense electric field in the GEM holes and second is in the semi-dipole field formed by the anodes and cathodes of the GMD. The conversion and collection fields are almost uniform: the field distortions due to the hole or strip structure penetrate only about 200 to 400 μm (two times the pitch) into the conversion or collection gap.

The electrons generated during the ionization drift toward the GEM holes following the electric field lines, while the ions drift toward the drift plane. When the electrons approach the GEM holes, they enter a region of increasing field strength, and are accelerated into the hole. Within the channels the electron will reach a region of very high electric field. Starting from a critical value of field, electrons begin to multiply in an avalanche, increasing exponentially along the channel (Eq. (2-3)) [33].

The field density becomes weaker at the bottom side of the hole. The electrons drift out of the channel, largely amplified by the avalanche process. The multiplication factor depends on the field density in the central region of the channel and its length [34].

Positive ions generated in an avalanche are collected by either the drift electrode or the top GEM electrode, whereas electrons are trapped at the GEM bottom or move toward the GMD anodes, the fraction depending upon the ratio between drift and collection fields for a given potential across the GEM.

The second avalanche happens around the GMD anodes. After the second avalanche, ions move toward the GMD cathode or toward the bottom GEM electrode, and electrons are collected by the anodes. The charge signal detected by the GMD anodes is given by:

$$Q = Mn_0e = M(E_{dep}/W)e \quad . \quad (2-5)$$

where, Q is the charge signal detected;

n_0 is the initial number of electrons produced by the incident photon;

e is the charge of the electron;

E_{dep} is the average energy deposited in the gas per interaction by the incident photon;

W is the average energy lost by the incident photon per ion pair formed. In principle, W is a function of the species of gas involved, the type of radiation, and its energy. But empirical observations show that it is not a strong function of energy but is remarkably constant for different types gases and radiation. It is about 26.2 eV for Ar and 21.5 eV for Xe [38];

M is the total gas gain from the hybrid, and is given by:

$$M = M_{gem} M_{gmd} T \quad . \quad (2-6)$$

where M_{gem} is the absolute gain of the GEM, M_{gmd} is from the GMD, and T is the charge transition coefficient that depends on the transparency and collection efficiency of the GEM:

$$T = f(\text{optical / electrical transparency, collection efficiency}) \quad . \quad (2-7)$$

The transparency and collection efficiency for the GEM are discussed in the next two sections.

2.2.4 Optical/Electrical Transparency of the GEM

The transmission probability of the primary electrons through a GEM hole is determined by the optical transparency and electrical transparency. The optical transparency is determined by the ratio of the open area to the total GEM area. Assuming a GEM mesh with cylindrical holes of diameter D at spacing P , its optical transparency is given by the expression [33]:

$$\tau = \pi D^2 / 4P^2 \quad . \quad (2-8)$$

For a GEM with $P = 140 \mu\text{m}$, $D = 70 \mu\text{m}$, the optical transparency is about $\tau = 0.20$.

The electrical transparency is defined by the proportion of field lines passing through the GEM holes, in contrast to those which terminate on the upper GEM electrode, and is controlled by the strength of the field in the conversion field relative to that in the holes [39]. For a high conversion field, some electric field lines terminate on the top GEM electrodes, so that some electrons are lost by stopping at the GEM top. On the other hand, the electrical transparency is higher for higher GEM voltages, and for electrodes with larger optical transparency. Bellazzini *et. al.* [39] measured the electrical transparency. The results showed that electrical transparency reached the maximum (100%) when using a conversion field of around 4 kV/cm. The GEM foil they used had a pitch 120 μm , Kapton thickness 50 μm , copper hole diameter 65 μm , Kapton hole diameter 30 μm . The collection field was fixed at 4.5 kV/cm. The potential across the GEM foil was 500 V. The filled gas was Ne/DME (50:50).

2.2.5 Collection Efficiency of the GEM

The collection efficiency is the ratio of the number of electrons that enter the multiplication region of the GMD (but have not yet been amplified by the GMD) to the total avalanche electrons produced in the GEM holes. It depends on the ratio between conversion and collection fields.

For a higher conversion field than a given collection field, some conversion field lines are directed toward the bottom GEM electrode instead of to the GMD. Cho *et. al.* [40] did a simulation on a GEM foil with Kapton diameter 40 μm and pitch 140 μm . The collection field was fixed at 5 kV/cm. The results showed that about 60% of conversion field lines were predicted to be drawn to the bottom GEM electrode at a conversion field of 15 kV/cm. In the experiments conducted by Bellazzini *et. al.* [39], the collection efficiency reached 80% with collection field 10 kV/cm. The geometry of the GEM, potential across the GEM and the fill gas were the same as that used in the experiments for testing the electrical transparency that I mentioned in the last section. Therefore, the

conversion field should be no larger than the collection field for maximal signal detection.

2.2.6 GEM Gain

The gain in the GEM has two categories. One is called the “absolute gain” (M_{GEM} in the equation (2-6)), and is defined as the ratio of number of avalanche electrons to initial electrons. The other is the “effective gain”, and is the ratio of the number of those electrons that reach the multiplication region of the GMD to initial charge, which includes the effect of both the transparency and collection efficiency of the GEM. In Eq. (2-6), the effective GEM gain is the factor of $M_{gem}T$.

From the last two sections (2.24 and 2.25), we can see that the effective gain is usually less than the absolute gain by an amount that depends on the field values. The effective gain increases exponentially with the voltage applied across GEM, and almost linearly with the strength of the collection field. For a given voltage, it is larger for narrower holes, but independent of the pitch [33].

2.3 Optimization of the GEM

The amplification of the GEM mesh depends on geometry and operating conditions. Hole diameter, pitch and geometry of the hole are determined by the manufacturing process. The thickness of the mesh is at present limited by the availability of high-quality metal-coated polymers that can be processed chemically [41].

At CERN, a range of hole diameters between 40 and 140 μm , and a pitch between 90 and 200 μm have been explored [33]. In order to obtain good manufacturing quality, e.g. avoid under-etching, the maximum hole diameter is usually limited to about two thirds of the pitch. Recently, it is found that producing GEMs on glass would bring more benefits [31].

Influence of hole diameter

As mentioned before, reducing the diameter of the GEM holes can increase the electric field in the GEM holes. Bachmann *et. al.* found that the gain increases considerably with decreasing diameter until around 70 μm , and reaches a plateau for lower values [33]. It was explained that, when the hole diameter is reduced below a value close to the GEM thickness, there are more avalanche electrons lost to the bottom GEM electrode.

Influence of pitch

The pitch plays no role in the gain characteristics, but combined with the hole diameter affects the electrical transparency, for electrons released in the drift volume, as well as the distribution of ions produced in the avalanches [41].

2.4 Charge Drift and Diffusion

Drift Velocity

If an external electric field is applied to the region in which ions or electrons exist in the gas, electrostatic forces will tend to move the charges away from their point of origin. The net motion consists of a superposition of a random thermal velocity together with a net drift velocity in a given direction. The drift velocity is given by [38]:

$$v = \mu \frac{E}{p} \quad . \quad (2-9)$$

where v is the drift velocity, E is electric field strength, p is gas pressure, μ is the charge mobility. For a given gas pressure, the higher the field is, the faster the drift velocity will be. So in order to collect the charge in a shorter time, a higher drift field is required.

Diffusion

When the electrons drift toward the GEM holes or the GMD, they are scattered in random directions, causing deviations from the mean trajectory. This leads to a broadening of the electron cloud in both the transverse and longitudinal directions, which is called diffusion. Electrons, starting to drift as a point-like cloud, show after a drift distance x a Gaussian distribution in the transverse and longitudinal direction with width defined by the standard deviations σ_t and σ_l respectively:

$$\begin{aligned}\sigma_t &= \sqrt{\frac{2D_t x}{v}} = \zeta_t \sqrt{x} \\ \sigma_l &= \sqrt{\frac{2D_l x}{v}} = \zeta_l \sqrt{x}\end{aligned}\quad . \quad (2-10)$$

Here, $D_t(D_l)$ is the transverse (longitudinal) component of the diffusion tensor. Commonly used are the transverse and longitudinal diffusion coefficients ζ_t and ζ_l , with dimension $(length)^{1/2}$.

2.5 Spatial Resolution

The intrinsic spatial resolution of the GEM/GMD detector

The spatial resolution of the GEM/GMD detector is intrinsically determined by the physical absorption process of the x-ray photon in the detector.

The absorption of an x-ray photon in xenon results in the ejection of a fast photoelectron from a xenon atom followed by one or more fluorescent x rays ($K_{\alpha\beta}$, $L_{\alpha\beta}$, etc.). The photoelectron then ionizes xenon gas along its path so that a charge cloud is formed before it stops. The distribution of this charge cloud over the GMD anodes is used to locate the coordinates of the incident photon. The size of the charge cloud gives an intrinsic limit to the spatial resolution that the detector can achieve.

There are mainly two categories of electrons generated in our detector after x-ray absorption: photoelectrons and Auger electrons. The range of these electrons controls the size of the charge cloud formed after the photoelectric effect. One measure of the electron range is the continuous slowing down approximation (CSDA) range. It is an integration along the actual path followed by the electron, and is given by [42]:

$$R = \int_0^{E_0} \frac{dE}{S(E)} \quad (2-11)$$

where E_0 is the initial energy of the electron, and $S(E)$ is the stopping power for the electron in xenon.

Figure 2.3: The range of the electrons with energies 10 – 50 keV in xenon. Calculated with Eq. (2-12).

The CSDA range gives the total track length but not the mean radial distance the electron moves from its point of origin, which is what we want to know. Bateman *et. al.*

give a formula for the range of electron with energy E (10 – 50 keV) in their Monte Carlo simulated physical model of the x-ray absorption processes [43]:

$$R = 0.2115Z^{0.26}E^{(1.265-0.0954\ln E)} \quad (2-12)$$

This formula uses units of MeV for energy and g cm⁻² for distance, and it can be used for high Z materials such as xenon. It takes account of the multiple scattering experienced by the electron, so it gives a better estimation than the CSDA range. The range for the electrons with energies 10 – 50 keV in xenon is plotted in Figure 2.3. It is observed that for the range of energies mentioned above (10 – 50 keV), the average distance from the origin point of the electron to the center of the charge cloud is about 60% of the range given by Eq. (2-12) [43], which generally limits the spatial resolution of our detector.

According to Eq. (2-12), the electron range increases rapidly with its energy. An electron's range increases by more than a factor of three when its energy doubles. So the spatial resolution degrades with electron energy, which is controlled by the energy of the incident x-ray photon and the energies of the shell electrons in xenon.

Other absorption processes in the gas simply cause degradation of the image. First, the re-absorption of fluorescent x-rays contributes to the spread of the line spread function and point spread function of the detector. Since they generate multi-peak events which are rejected during the event analysis, their contribution is negligible in our case. Second, photon scattering of the GEM foil would generate a uniform background.

The effect of the GEM hole structure

The charge centroid algorithm applied in the GMD to find the location of each photon interaction makes the spatial resolution of the GMD better than the anode pitch (200 μ m). With the GEM coupled to the GMD, the main concern is that, when the primary electrons drift toward the GEM holes, they are "sampled" by the discrete holes at 140 μ m pitch. Is this going to introduce significant distortion in finding the centroid of the electron cloud? The answer should be no. The diffusion of electrons in the conversion and collection gaps would minimise the effect of the GEM hole structure. For a electric

field of 2 kV/cm, the σ of the charge cloud after 2 mm drift is $> 150 \mu\text{m}$ for Xe:CH₄ (9:1) at 1 atm. The average σ of the charge cloud in the conversion gap (3.9 mm) was calculated to be about $200 \mu\text{m}$ by using the simulation model described in Appendix A. This means that the charge cloud produced in the conversion gap would cover at least two GEM holes. The effect of the discrete sampling of the GEM holes will be less when more GEM holes are covered. Further diffusion of those avalanche electrons in the collection field would help to minimise the effect further.

The calculated centroid versus the GEM hole position with respect to the position of the GMD electrodes was studied using the simulation model described in Appendix A. Figure 2.4 and 2.5 give two results of the simulation at 1 atm in xenon. In the simulation, the centroid of the charge cloud produced in the conversion gap was known and fixed at one point, and the GMD position was fixed. The GEM was moved along the GMD readout direction to change the relative position between the GEM holes and the GMD electrodes. The geometries are shown in Figure A.1 and A.2.

The result shown in Figure 2.4 is for the geometry shown in Figure A.1, the centroid of the charge cloud was at GMD anode 8 (at 1.4 mm, the anode 1 was at the origin of the coordinates). The initial position of one of the GEM holes was at the same position as the charge cloud centroid and thus of the anode 8. The calculated centroid for each GEM position was plotted versus the moving distance of the GEM from its initial position to the right, i.e. the relative position between the anode 8 and the GEM hole which was at the anode 8 at the beginning. As shown in Figure 2.4, the calculated centroid varies periodically when the GEM holes shift respect to the GMD anodes.

Figure 2.5 shows the same periodic variation for the bias of the calculated centroid with the geometry shown in Figure A.2. In this case, the centroid of the charge cloud was fixed at GMD cathode 7 (1.3 mm) and the GEM was moved with respect to this cathode to the right. The initial position of one of the GEM holes was aligned with the cathode 7.

From the two simulations shown in Figure 2.4 and 2.5, we can see that the variation period of the calculated centroid is the GEM pitch $140 \mu\text{m}$. The maximum bias of the calculated centroid is less than $1 \mu\text{m}$. The smallest bias happens when the GEM holes distribute symmetrically with respect to the centroid of the charge cloud. So the introduction of the GEM foil does bring errors on the centroid calculation and the error is

Figure 2.4: The effect of the different relative position of the GEM holes to the GMD electrodes on the bias of the centroid calculation. The centroid of the charge cloud is aligned with one GMD anode.

Figure 2.5: The effect of the different relative position of the GEM holes to the GMD electrodes on the bias of the centroid calculation. The centroid of the charge cloud is aligned with one GMD cathode.

GEM hole structure dependent. Compared with the electronic noise (9.5 μm) and statistical error of the charge cloud (7.4 μm) which were calculated by D. Gobbi [24], the bias introduced by the GEM can be negligible.

2.6 Energy Resolution

The energy resolution of a detector is the ability to distinguish individual lines in the spectrum. Assume that the formation of each electron is a Poisson process. If this were the only source of fluctuation in the signal, the response function of the detector for a mono-energetic line emitted by the source would have a Gaussian shape. The conventional expression for the energy resolution uses the full width at half maximum (FWHM) of the peak:

$$R = \frac{\Delta E}{E} = \frac{FWHM}{\text{peak position}} = \frac{2\sqrt{2\ln 2}\sigma_{\text{peak}}}{\text{peak position}} = \frac{2.35\sigma_{\text{peak}}}{\text{peak position}} \quad (2-13)$$

In a gas detector, the fluctuation in the output signal for a fixed gamma energy originates from the statistical fluctuations in the following phases in the signal development: the number of primary electrons, the interaction of the primary electrons in the conversion region, the avalanche, the noise of the preamplifier and pedestal shifts (pedestal shifts are shifts in the DC-offset of the signal, which can occur when the outputs from several channels are multiplexed).

Neglecting contributions that originate from the read out electronics, the intrinsic energy resolution of a proportional counter is determined by fluctuations in the charge $Q = Mn_0e$, and thus from variations in the gain M and the number of primary electrons n_0 . Assuming that these two distributions are independent, then the intrinsic energy resolution is given by:

$$(\sigma_E / E)^2 = (\sigma_Q / Q)^2 = \left(\frac{\sigma_{n_0}}{n_0} \right)^2 + \left(\frac{\sigma_M}{M} \right)^2 = \frac{1}{n_0} \left(F + \frac{1}{M} + b \right) \quad (2-14)$$

with b the variance of the Polya distribution (typical value of 0.4-0.7 [38]), that describes the single electron gain distribution (see Appendix B). The parameter F is the Fano factor, which expresses the variation in the number of primary electrons at the conversion. Dias *et al.* [44] did a Monte Carlo calculation for F in xenon, which showed that it is energy dependent. It ranges from 0.17 to 0.32 for x rays in the energy range of 0.1 to 25 keV and has sharp increase near the xenon absorption edges. Since the Fano factor is relatively small, the main factor influencing the energy resolution is the gain variation in the avalanche, which depends not only on the gas but also on the operational conditions of the detector [45].

In the case of the GEM/GMD configuration, it is the fluctuation in the combined gain of the GEM/GMD that determines the energy resolution. For incident x rays depositing energy E_{dep} , the number of the primary electrons is: $n_0 = E_{dep} / W$ (W is the mean energy to produce an ion pair). Substitute this expression and Eq. (2-14) into Eq. (2-13), to yield the expression for the intrinsic energy resolution R_{int} of the GEM/GMD:

$$R_{int} = 2.35 \sqrt{\frac{(F + f)W}{E_{dep}}} \times 100\% \quad . \quad (2-15)$$

where $f = \frac{1}{M} + b$. It is a factor that is determined by the variation of the combined gain of the GEM/GMD (M).

For a gas detector, the best energy resolution that can be achieved is limited by the W -value and the Fano factor F [46]:

$$R_{limit} = 2.35 \sqrt{\frac{FW}{E_{dep}}} \quad . \quad (2-16)$$

In order to achieve energy resolutions that approach this limit, care must be taken to minimize potentially harmful effects of electronic noise, geometric non-uniformities in the detector, and variations in the operating parameters of the detector. Significant

operating parameters that can affect energy resolution are gas purity, gas pressure, and stability of the high voltage applied to the detector [38].

In practice, factors other than n_0 , F and b add to the spread in the output amplitude [31]. These include inhomogeneities in the electric field at the edge of the detector, malfunctioning areas on a non-perfect substrate, or non-complete charge collection due to the absorption of the photoelectron in one of the walls of the detector.

2.7 Detector Efficiency

Due to the window attenuation and finite conversion gap, not all of the incident photons interact with xenon in the detector. The fraction of the incident photons that interacts is the quantum efficiency (η) of the detector:

$$\eta = \frac{N_{interact}}{N_{in}} \quad . \quad (2-17)$$

where the N_{in} is the number of incident photons, and $N_{interact}$ the number of photons that interact with xenon. The η is determined by the product of xenon detector depth and pressure. Since the conversion gap and window material are kept the same as before, the η of the hybrid detector should be the same as that of the GMD examined previously.

One of the advantages for a photon-counting detector is that ideally its detective quantum efficiency (DQE) is equal to η . The DQE of a detector tells us how the signal-to-noise (SNR) ratio varies through the system. It is defined by:

$$DQE = \left[\frac{SNR(image)}{SNR(in)} \right]^2 \quad . \quad (2-18)$$

where $SNR(in)$ is determined only by the mean photon arrival rate and the time period of observation, and $SNR(image)$ is the SNR measured on the final image.

The DQE of an energy integrating detector is degraded by the Swank factor (η_{Swank}) [1]:

$$DQE = \eta \frac{(\overline{E_d})^2}{(\overline{E_d})^2} = \eta \eta_{Swank} \quad . \quad (2-19)$$

Typically, the Swank factor is about 0.8 ~ 0.9 [1]. It is determined by the distribution of the energy deposited in the detector.

Eq. (2-19) does not apply to a photon counting detector, since the signal here is the number of photons, which follows a Poisson distribution. For a photon counting detector, the $SNR(image)$ is determined by the following equation:

$$SNR(image) = \frac{N_{image}}{\sqrt{N_{image}}} = \sqrt{N_{image}} \quad . \quad (2-20)$$

where N_{image} is the number of photons that contribute to the image. Similarly,

$$SNR(in) = \frac{N_{in}}{\sqrt{N_{in}}} = \sqrt{N_{in}} \quad . \quad (2-21)$$

Substituting Eq. (2-20) and (2-21) into Eq. (2-18), we get the DQE for a photon-counting detector in the ideal case where every photon which interacts is used for the image:

$$DQE = \left[\frac{SNR(image)}{SNR(in)} \right]^2 = \frac{N_{image}}{N_{in}} = \frac{N_{interact}}{N_{in}} = \eta \quad . \quad (2-22)$$

Typically, since there is a set of event rejection criteria applied in the event analysis, the DQE of a photon counting detector is less than the quantum efficiency:

$$DQE = \frac{N_{image}}{N_{in}} = \frac{(1-r)N_{interact}}{N_{in}} = (1-r)\eta \quad . \quad (2-23)$$

where r is the number of events rejected in the event analysis. In our detector it is about 5% ~ 15%, so only 85% ~ 95% of the detected photons are included in the image.

Chapter 3

Prototype Imaging System with GEM/GMD

The GEM is coupled to the GMD as a pre-amplification structure to form a hybrid detector. The whole imaging system works on the principle of scanned projection radiography (SPR). In this chapter, the GEM/GMD hybrid imaging system is described. The techniques applied to the GEM, including the test, assembly and the high voltage application to the GEM are introduced. The apparatus of the bench-top system, its electronic equipment and the fill gases are described.

3.1 The Imaging System with GEM/GMD Hybrid Detector

3.1.1 Geometry

Scanned Projection Radiography System

Figure 3.1 shows the geometry of the scanned projection radiography (SPR) system built with the GEM/GMD hybrid detector. A stainless steel pressure vessel with a 1.5 mm thick Lexan window is used to house the GEM/GMD hybrid and the drift plane. There is a vertical stage between the x-ray tube and the vessel on which the object is fixed. A computer-controlled motorized micrometer on the stage can bring the object up and down. In this way, the object is scanned by a fan beam that is defined by a horizontal fan-beam slit placed between the x-ray tube and the vertical stage. So the imaging system can generate 2D images — one image coordinate is provided by the GMD anodes, and the

Figure 3.1: The SPR imaging system built with the GEM/GMD hybrid detector. Measurements are to the focal spot of the x-ray tube and to the GEM top.

Figure 3.2: Diagram for the geometry of the GEM/GMD hybrid detector. The HVs presented in the diagram are for Xe:CH_4 at 4 atm, and the gas gain is 135.

second one by scanning. An anti-scatter slit is placed right before the drift plane to remove the x rays scattered out of the fan beam.

The geometry of the imaging system is carried over from that of the previous GMD imager, except that the GEM is coupled to the GMD and an alignment frame is added to the system. The dimensions labeled in Figure 3.1 are a bit different from the previous system, but the geometry magnification factor is still about 1.1.

Geometry of the GEM/GMD Hybrid Detector

As shown in Figure 3.2, the GEM is placed between the GMD and the drift plane, an aluminized Mylar sheet. They are housed in a pressure vessel, with the frame of the drift plane touching the Lexan window of the vessel. The sensitive area of the GEM foil is $20 \text{ mm} \times 70 \text{ mm}$. There is a copper strip extending out from the GEM electrode on each side of the foil, to which the HV is applied. One of the advantages of the GEM devices is that they are almost self-supporting, therefore permitting the realization of light detectors with minimum frame thickness. In our case, the frame of the GEM is made of G10, and it is 1 mm thick. The drift plane, GEM, and GMD are individually glued on thin frames, and supported with insulating screws and nuts. These nuts also serve as spacers to define the gaps. The conversion gap between the GEM top and the drift plane is 3.9 mm, where the ionization happens. The conversion gap is kept the same as in the previous GMD imager so that we can compare the performance between the GEM/GMD and the GMD only. The collection gap between the GEM bottom and the GMD is 1.8 mm, where the electrons are extracted from the GEM holes and collected by the GMD anodes.

The sensitive volume in our detector is $3.2 \text{ mm} \times 50 \text{ mm} \times 3.9 \text{ mm}$ (width (x) $\times$ height (y) $\times$ depth (z), Figure 2.2). The height is given by the GMD. Since we only use the central 16 anodes of the GMD and they have $200 \mu\text{m}$ pitch, the width is 3.2 mm.

3.1.2 GEM foil Fabrication

The fabrication technology for the GEM was developed by the CERN Surface Treatment Service, where our GEMs were manufactured. Since the number of holes on

one foil is very large (about 46,000 on $3 \times 3 \text{ cm}^2$), techniques which allow simultaneous hole production are required. So far, the available technologies include: wet or dry etching, ultrasonic drilling or grinding, and laser drilling.

Typically, a GEM mesh is produced by conventional photolithographic methods followed by chemical etching [39]. First, the pattern of holes is engraved by conventional photolithography on the copper on both sides of the foil. Then the hole pattern is used as the mask for the etching, and the channels are opened with a Kapton-specific solvent from both sides of the foil. Due to the chemical process employed, the GEM holes have a double-conical shape with the diameter in the center of the Kapton slightly smaller than that at the copper surface.

3.1.3 GEM Testing Procedure

We tested the GEM in our lab in two steps before mounting. First, in the clean room, the resistance in air between the two sides of the GEM foil is measured with an ohmmeter, and it is accepted if the value exceeds $2 \text{ G}\Omega$. Second, since the HV power supply is not available inside the clean room built in our lab, the GEM is mounted and sealed in the vessel with air in it, and is brought out of the clean room. The high voltage crossing the GEM is fed into the vessel through the high voltage connectors mounted on the cover of the vessel, and there is a high value protection resistor connected in series with the GEM. The leakage current is measured as the voltage is slowly increased. It is accepted if the leakage current is below $\sim 5 \text{ nA}$ at 500 V between the electrodes. This corresponds to an inter-electrode resistance above $100 \text{ G}\Omega$.

3.1.4 Assembly

The GEM foil is always handled in the clean room with gloves. Contact with dirt or hard surfaces was avoided as this could generate shorts.

Our GEM is very small ($20 \times 70 \text{ mm}$). It is glued on a supporting G10 frame. In order to get uniform gain over the GEM, the foil has to be stretched well when it is glued on the final frame. First, we tension-taped the foil on a temporary frame which was the

same as the final frame, then overlaid it on the final frame previously coated with epoxy. There were two screws on the temporary frame at opposite corners, which helped to align the sensitive area of the small GEM foil with the final frame. So the GEM foil was sandwiched by the two frames, and they were compressed with clamps. They were left in the oven for about 2 hours at 80°C. This guarantees good mechanical tension of the GEM at room temperature.

Before the GEM foil was assembled in the final detector, it was gently blown with nitrogen in the clean room. Then the assembled detector was left for several hours on open gas flow. Before gas filling, the vessel was evacuated with a mechanical pump. The assembled detector was exposed to vacuum for a few minutes, which was found to improve its operation in terms of the maximum attainable gain [32]. It might be because water absorbed in the Kapton was removed.

Figure 3.3: Diagram of the connectors mounted on the vessel cover and their functions.

3.1.5 High-Voltage Application

In our hybrid detector, two Bertan HV power supplies, models 380 and 1720 (Bertan Associates Inc.), each with two independent HV outputs, are used to supply the high voltage to the drift plane, the GEM electrodes and the GMD cathode.

We need three feed-through connectors to feed three high voltages into the pressure vessel to the drift plane, the GEM and the GMD cathode. We have three BNC connectors and two Bendix connectors (PT07H-12-10P and PT07H-12-8P) on the cover of the pressure vessel. The orientation of these connectors on the vessel cover is shown in Figure 3.3. One of the BNC connectors was used to read out the GMD cathode signal before. In order to get an extra pin to read out the cathode signal and save one BNC connector for the HV application, we changed one of the two Bendix connectors on the vessel cover from eight pins to ten pins. One of the two extra pins is used to read out the cathode signal, the other one is left floating. The remaining eight pins are still used to read out signals from eight anodes. The other Bendix connector is left unchanged. Its eight pins are used to read out the signals from the other eight anodes.

GEM

There are two methods for powering GEMs: 1) Direct application of the required voltages to each of the two electrodes through independent, current limited HV power supplies with a high-value protection resistor (typically $10\text{ M}\Omega$), as shown in Figure 3.4 (a); 2) A single power supply with a resistive divider network to provide the potential across the GEM, as shown in Figure 3.4 (b).

Method one is convenient for systematic studies, since it permits one to vary the potential difference between any pair of electrodes and keep all others constant. In order to avoid exceeding maximum local differences, the voltages have to be ramped very slowly. In the case of discharges, the current from one unit can feed into the other with unpredictable results. A solution to this problem is to connect a large value resistor to ground, through which the leakage current from each unit will go [33]. We did not use this method because this method can destroy the GEM if one of the two supplies trips leaving the other HV supply on. This would increase the voltage across the GEM suddenly and destroy the GEM.

We chose method two, i.e. the operating voltages are applied to the GEM through resistive dividers. The value of each resistor is shown in Figure 3.5. The Bertan 1792

power supply is used to supply the high voltage. The ratio of the voltage difference across the GEM to the voltage at the GEM top is fixed at 2:5.

Method two is safer than method one because any sudden HV supply trip produces 0 V across the GEM. However, the resistor chain method to supply GEM high voltages can be used only if the current induced by x ray absorption and avalanches is small. This was the case for our measurements. If the x-ray flux were very high (such as was used by D. Gobbi [24] to demonstrate high count rate capability of the GMD), the radiation induced current in the detector could be significant. The increased current flowing through the voltage divider resistors would be accompanied by a voltage drop across the GEM leading to a lower gain. Method two cannot be used for high rate operation. However, it was acceptable for our work and we used it because it minimizes the possibility of destroying the GEM as stated earlier.

Drift Plane, GMD Anodes and Cathodes

The drift plane and the GMD cathodes are at high voltage. As shown in Figure 3.5, the high voltage for both the cathodes and drift plane is filtered through an RC circuit ($RC = 1.2$ ms) to filter the fluctuation from the power supplies. The central 16 cathodes are grouped together and held at high voltage. The central 16 anodes are grounded individually.

In order to provide a uniform collection field for the central 16 anodes, a group of eight cathodes to either side of the central sixteen cathodes is held at high voltage, and a group of eight anodes to either side of the central 16 anodes is grounded.

The circuits used to supply the high voltage to the drift plane and the GMD cathode, and the ones used to read out signals from the GMD anodes and cathodes were assembled before I started my work on this project. The values of these resistors and capacitors were not changed [24].

The Bertan 380 is used to supply HV to the GMD cathode and to the drift plane. The voltage must be ramped gradually. Meanwhile, the output of the cathode is monitored on the scope. If breakdown appears, the HV has to be decreased.

Figure 3.4: Schematic of the two methods to supply voltage to the GEM: (a) use individual HV supplies; (b) use resistor divider.

Figure 3.5: Schematic of the high voltage application in the GEM/GMD hybrid detector. The part within the dotted line is housed in the pressure vessel.

3.2 Apparatus

Since the geometry of the imaging system is carried over from the GMD imager, most of the components used in the system are maintained. As shown in Figure 3.1, the apparatus of the system consists mainly of the x-ray tube, fan-beam slit, object stage, anti-scatter slit, the pressure vessel, and the alignment frame. I designed the alignment frame. The rest of the apparatus was built before I started to work in the lab. Please refer to D. Gobbi's thesis [24] for details.

50 kV X-Ray Tube

The x-ray tube is an Oxford XTF5011 5-50 kV, 0-1 mA tungsten-target x-ray tube (Oxford Instruments Inc., 276 Technology Circle, Scotts Valley, CA 95066 USA) with a $77\text{ }\mu\text{m} \times 196\text{ }\mu\text{m}$ focal spot.

In my experiments, the power of the tube was kept $\leq 75\%$ of full power due to the heat capacity of the tube. The tube current was chosen according to tube voltage used.

Fan-Beam Slit

Two pieces of lead are fixed on an aluminum stage to form the fan-beam slit. Two small foils are used to define the height of the fan-beam slit. It is $80\text{ }\mu\text{m}$ in our system. It has to be checked regularly and cleaned by blowing with high-pressure air.

Object Stage

There are two micrometers on the object stage to move the object vertically and horizontally within the object plane. In this way the object is scanned by the fan beam. The horizontal micrometer is tuned manually, and the vertical one is controlled by the computer.

Anti-Scatter Slit

Two small pieces of lead are glued to a U-shaped sheet of steel to form a $120\ \mu\text{m}$ lead slit. It is used to eliminate those x-ray photons scattered out of the fan beam, and to define the field of view of the detector. It is placed right in front of the drift plane, about 5.5 mm from the GEM top electrode and 7.5 mm from the GMD print.

Pressure Vessel

The GEM/GMD hybrid detector is housed in a 6-liter cylindrical stainless-steel pressure vessel. It was tested to 9 atm in 1999 by Philippe Gravelle, the technician in our lab.

Figure 3.6: Diagram of the alignment setup.

Alignment Setup

Alignment is very critical in the experiments, especially in the MTF measurement. It was done in three steps. First, the front face of the pressure vessel and the object plane have to be parallel to each other, and perpendicular to the x-ray beam; second, the fan-

beam slit and the anti-scatter slit have to be aligned; third, the sensitive area of the detector has to be at the center of the x-ray beam, i.e. aligned with the focal spot.

In the previous setup, there was not a reference point or plane for the alignment. I designed and built an “alignment frame”, which is shown in Figure 3.6. Two square aluminum bars (110 cm long) with screws at each end are fixed at two sides of the system, along the longitudinal direction and perpendicular to the vessel window. The two bars are movable with the help of the screws at each end, and they are used as the reference. First, they are tuned to be perpendicular to the front plane of the x-ray tube with the help of a square (the x-ray tube is fixed on the optical bench). Then the object plane and the vessel window can be tuned to be perpendicular to the bar with the square. In this way, we know the object plane and the detector window are parallel to each other and perpendicular to the x-ray beam.

The fan-beam slit is mounted on a micrometer stage, which can be moved vertically. The maximum count rate will be reached when the fan-beam slit and the anti-scatter slit are aligned. So the count rate at different micrometer readings is plotted, and the fan-beam slit is fixed at the position for the maximum count rate.

There is a micrometer under the pressure vessel. It can move the vessel laterally. The maximum count rate is obtained when the detector is aligned with the focal spot. So the count rate at different vessel positions is plotted, and the vessel is fixed at the position at which the maximum count rate is obtained.

Once the alignment is done, the two bars can be fixed with nuts to keep the alignment unchanged during the experiment, which is more solid and reliable than before.

3.3 Electronics

A block diagram of the imaging electronics is given in Figure 3.7. The charge signals from 16 GMD anodes are amplified by the pre-amplifiers (QPA02) and amplifiers. Then they are digitized in the analogue-to-digital converters (ADC) and transferred to the computer to generate images. The imaging scan and data acquisition are controlled by a 40 MHz 80386 PC through a CAMAC interface. All the raw data are saved onto a 6 Gbyte space in the hard drive of the Unix “Bragi” machine.

Figure 3.7: Block diagram of the imaging electronics.

Figure 3.8: Block diagram of the simple pulse height analysis system used in the gain and spectrum measurements.

At this stage, we mainly concerned about the physical performance of the detector. So our imaging system was built with off-shelf electronic modules. The electronics was built before I came to the lab, but I had to make them work properly again.

Though the imaging electronics can provide energy information for each image, a commercial pre-amplifier and amplifier EG&G Ortec 142PC and 450, and an Ortec 916 MCA are used to test the energy response of the imaging system for their low noise. As shown in Figure 3.8, a patch board allows the 142PC to be connected to any combination of the 16 anodes or to the cathodes. The pulses from the 142PC are shaped by an Ortec 450 amplifier and then sent (via 6 V positive unipolar output) to an Ortec 916 MCA card that is housed in the PC.

Pre-amplifier QPA02

The QPA02 charge sensitive preamplifiers were developed by Tom Zimmerman at Fermilab [47]. These amplifiers accept either positive or negative input and provide mirrored positive and negative output to drive a 50 Ω transmission line. There are 8 channels per chip, and each preamplifier board (also developed by T. Zimmerman) has 128 channels. There are two protection diodes of opposite polarity on each preamplifier input as a precaution against high-voltage transients.

The QPA02 amplifiers have a nominal 6 ns rise time and 35 ns recovery time for an impulse input when the input capacitance is 20 pF. The nominal maximum gain is 500 mV/ μ A for a constant current input, and 17 mV/fC for an impulse charge input.

Amplifier Board

The differential signal from the QPA02 is carried via a 5 m shielded ribbon cable to the amplifier board which houses 64 Signetics NE5539 operational amplifiers (17 of which are used, 16 for anodes and 1 for cathode). This amplifier board was designed by Ernie Neuheimer. It amplifies the signals from the QPA02 into a negative unipolar signal in the range of 0-0.5 V. The quoted bandwidth for these amplifiers is > 20 MHz.

The amplifier board used in the GMD imager was not available when I started my work on this project. The one that was available did not work at the beginning. I did the troubleshooting of the board with the help of Ernie Neuheimer. This board was isolated from the imaging electronics and tested independently. Test pulses were injected from a pulser, and the whole circuit on this board was traced. Oscillation problem showed up when this board was mounted on the rack and connected with the QPA02. It was found that these were mainly due to the following reasons.

First, there are digital and analog circuits on the same board. The analog part is the operational amplifiers, and the digital part is the discriminators where the analog signals from the Opamps are digitized to binary signal (0 and 1). Since the digital ground and analog ground were not isolated well, fluctuations on the digital circuit entered the analog circuit and triggered the oscillation. Some inductors and capacitors were added to the circuit to get rid of the oscillation. Second, the amplification factor of this board was too high. It was decreased from 10 to 3. Third, to get a negative unipolar signal from each channel, a specific polarity for each input of the Opamp NE5539 is required. The polarities of the output signals from the QPA02 were not matched to the requirement. A patch board was designed and made by myself to feed into the Opamp NE5539 each differential signal output from QPA02 (32 channels from the 16 anodes and 2 channels from the cathode) with correct polarity. Finally, the threshold of those discriminators on the amplifier board was set very high (~ 170 mV) which was found helpful in stopping the oscillation.

Trigger Circuit

The cathode signal is used as the trigger signal for the whole imaging electronics. The circuit of the trigger system is shown in Figure 3.9. The cathode signal is fed into a discriminator (Lecroy 623B) through a Linear Fan In/Out module (Lecroy 428F). When the amplitude of the cathode signal is higher than the threshold set on the discriminator, this event is regarded as a valid event. Then the Gate Generator (#2) (Lecroy 222) is turned on to block the consequent events until the NIM driver (Lecroy ND027) sends a

pulse to the Gate Generator indicating that the data acquisition cycle is completed. The 20 ns delay ensures that the trigger pulse does not veto itself.

Circuit for Dead-Time Correction

The period during which the Gate Generator is on, as mentioned above, is called the “dead time” of the system. Events which happen during this time are not registered by the electronics. Two scalars (GEC-Elliott Sr1608) are employed in our system to correct the losses.

As shown in Figure 3.9, the gate generator (#1) (Lecroy 222) is used as a pulser. Once the power is on, the connector has to be shaken gently to start the self-triggering through a delay line to provide 385 pulses per second. The total number of the pulses is the real time, and the number of pulses counted when the system is not busy is the live time. The dead time correction is realized in the event analysis software.

Figure 3.9: Block diagram of the trigger circuit and the real-time/live-time scalars.

Analog-to-Digital Converter (ADC, Lecroy 2249W)

The job to be performed by the ADC is to generate a digital number that is proportional to the amplitude of the pulse presented at its input.

The ADC module LeCroy 2249W used in our system only accepts negative polarity signal. The charge signal from the amplifier board is digitized to a maximum 11 bits of precision by integrating the input current over a gate width which is set to 100 ns. The signals from anodes and cathode are delayed 50 ns before they are fed into the ADC to ensure that the ADC does not miss the leading edge of the signal pulses.

3.4 Fill Gases

The fill gases consist of a noble gas and an organic quencher, and they are mixed together in a 9:1 ratio in the vessel by partial pressure. Two fill gas mixtures were used: argon:methane (Ar:CH_4) and xenon:methane (Xe:CH_4). The former mixture was filled into the vessel first after the detector was assembled, and was mainly used to test the performance of the new imaging system.

The Xe:CH_4 mixture was used for imaging. Since it has the highest atomic number within the stable noble gases, xenon has the highest photoelectric absorption coefficient. Besides, its K shell photoelectrons have lower energies and consequently lower ranges. For example, for the x-ray energy of 40 keV, the range of a photoelectron in argon at 1 atm is ~ 14 mm, but ~ 0.3 mm in xenon [43].

Chapter 4

Experiments and Results

In our detector development lab, the physical characteristics of the GEM/GMD hybrid detector were investigated, including the gain, the energy resolution and the spatial resolution. Each of these parameters was measured for Xe:CH₄ 9:1 at each of 1, 2, 3 and 4 atm. In this chapter, the experimental methods are described and results are presented. Finally, some images obtained with the hybrid detector are shown.

4.1 Noise Reduction

During the whole experiment, the pick up noise level on the signal had to be kept at a reasonably low level, and noise reduction is not a minor task. The following is a list of the main steps to reduce noise that I did in the experiment.

- The 3M connector on the pre-amplifier board introduced spike-like noise, which was due to a loose connection. Tape was used to get a better connection to reduce this noise.
- The Bendix connectors on the cover of the pressure vessel introduced burst noise. A plastic cable strap was used to get a better connection and the noise was gone.
- The pressure vessel and everything connected with the vessel had to be insulated from the bench.
- High frequency noise on the long signal cable and power supply cable was reduced by adding ferrite cores.

4.2 Gain Measurement

The gain was measured from pulse height analysis. The simple pulse height analysis system is shown in Figure 3.8. Amplifiers EG&G Ortec 142PC and 450, and Ortec 916 MCA (embedded in the PC) were used.

4.2.1 System Calibration

Before the gain measurements, the system, i.e. the amplifiers and MCA, was calibrated using a test input to determine the pulse height scale of the analysis system, so that the gain values obtained from this analyzer could be compared to values taken at other amplifier and MCA settings.

Ideally, the preamplifier and amplifier that are used to read out the signal from the detector would be sufficiently linear, and the MCA would perform a perfect linear conversion of pulse height to channel number. Under these conditions, a plot of channel number versus pulse height would be a simple straight line:

$$chn = ch0 + AQ \quad (4-1)$$

where Q is the charge signal collected by the detector and is the input signal of the analyzer, chn is the channel number corresponding to the size of charge signal Q , and $ch0$ is the zero offset of the MCA.

To test the linearity and determine the zero offset of the analyzer, a pulser is able to provide points for a calibration plot. The pre-amplifier EG&G Ortec 142PC has a test input with a nominal 1 pF input capacitor. A series of pulses with known amount of charge Q are injected into the 142PC from a pulser ($Q = VC$, V is the voltage of the test pulse, and C is equal to 1 pF), and a series of corresponding Gaussian pulses are captured by the MCA. From the MCA, the channel number of the peak of each Gaussian is calculated. By applying a linear fit to these points (Q, chn), $ch0$ and A are obtained. Figure 4.1 gives an example of the calibration plot of the analyzer with a test pulser.

Figure 4.1: A calibration plot of the analyzer with a test pulser.

In order to determine the energy scale of the pulse height distribution, a calibration source, e.g. ^{55}Fe or ^{241}Am , is needed. These sources emit characteristic lines with known energies, so we can calculate the primary charge q according to:

$$q = eE_{dep} / W \quad , \quad (4-2)$$

where E_{dep} is the energy of each known spectral line, and W is the energy for producing one ion pair. Denoting the gain of the detector as M , then the charge signal detected by the detector is given by:

$$Q = Mq = (Me/W)E_{dep} = \bar{A}E_{dep} \quad . \quad (4-3)$$

Substituting (4-3) into (4-1), we get the calibration line for the channel number versus energy deposited:

$$chn = ch0 + BE \quad (4-4)$$

So we can calibrate $ch0$ and B by several known spectrum lines. The more lines we use, the more accurate the calibration.

Figure 4.2: the setup for the measurement.

4.2.2 Method for the Gain Measurement

The gain of the detector was measured with a calibration source ^{241}Am . When measuring the gain, the absorption spectrum was captured by the hybrid detector and recorded by the MCA. Each peak in the spectrum corresponds to a specific amount of charge q deposited in the hybrid detector, which is calculated by Eq. (4-2). We know the relationship between the MCA channel number and the charge injected into the

preamplifier, i.e. the charge collected by the detector, which is given in Eq. (4-1). Combining these two equations provides an expression for the detector gain M :

$$M = \frac{Q}{q} = \frac{(chn - ch0)/A}{eE/W} . \quad (4-5)$$

In Eq. (4-5), $ch0$ and A are determined by calibrating the (preamplifier + amplifier + MCA) using a pulser (as shown in Figure 4.1), and chn is the channel number into which the centroid of the spectrum line with characteristic energy E falls.

During the gain measurement, the anti-scatter slit was in place. The ^{241}Am source is saved in a cylindrical container. A slit collimator was placed in front of the source container to define the beam. The distance between the source and the collimator is about 46.4 mm, and there are about 87.5 mm between the source and the drift plane, as shown in Figure 4.2.

4.2.3 Results

4.2.3.1 Detector Gain vs. GEM Voltage and GMD Cathode Voltage

The gas gain in the GEM/GMD is very complicated. The GEM gain is not only related to the field in the holes but is also affected by the outside field, i.e. the conversion field and the collection field. In order to get maximum gain, these fields have to be optimized, i.e. the collection field should be much higher than the conversion field. In our system, since the GEM voltage is supplied by a resistor network, the highest collection field in terms of safe operation for the GEM is limited by the voltage across the GEM:

$$E_{col} = \frac{V_b - \bar{V}_c}{d} = \frac{1.5\Delta V_{gem} - \bar{V}_c}{d} . \quad (4-6)$$

where V_b is the voltage at the GEM bottom; ΔV_{gem} is the potential across the GEM, the factor 1.5 is determined by the resistor network; d is the thickness of the collection gap

(1.8 mm); $\bar{V}_c$ is the average voltage on the GMD print, it is determined by the GMD cathode voltage V_c , the width of the GMD anode and cathode, and the gap between the GMD anode and cathode. For $\Delta V_{gem} = 500$ V, the collection field (E_{col}) could reach 4.2 kV/cm at maximum (assume $V_c = 0$). For a given ΔV_{gem} , the collection field would be reduced by increasing V_c to get gain from the GMD. Bellazzini *et al.* [39] found that an efficiency of 80% can be reached with $E_{col} = 10$ kV/cm in Ne/DME (50/50). Therefore the gas gain in our system has not been exploited completely.

The detector gain versus the GEM voltage (ΔV_{gem}) and the GMD cathode voltage (V_c) was measured in Xe:CH₄ from 1 to 4 atm and in Ar:CH₄ at 1 atm. Table 4.1 lists the value of the conversion field for each measurement, and the collection field at the highest gas gain reached for each measurement. When calculating the collection field, $\bar{V}_c$ was assumed to be about $\frac{1}{2}V_c$.

Table 4.1 Conversion field and collection field (at the highest gas gain) applied for the gain measurement

	Conversion field (kV/cm)	Collection field (kV/cm)
1 atm Xe:CH ₄	1.8	3.0 ($\Delta V_{gem} = 450$ V, $V_c = 290$ V)
2 atm Xe:CH ₄	1.8	3.7 ($\Delta V_{gem} = 576$ V, $V_c = 380$ V)
3 atm Xe:CH ₄	1.9	4.4 ($\Delta V_{gem} = 688$ V, $V_c = 480$ V)
4 atm Xe:CH ₄	1.9	5.5 ($\Delta V_{gem} = 830$ V, $V_c = 500$ V)
1 atm Ar:CH ₄	1.8	3.1 ($\Delta V_{gem} = 445$ V, $V_c = 200$ V)

Figure 4.3 to 4.6 show the combined gas gain curves for the GEM coupled to the GMD in Xe:CH₄ at 1–4 atm, and Figure 4.7 shows the gain curves in Ar:CH₄ at 1 atm. All the gain curves for GMD alone are reproduced from D. Gobbi's thesis. Compared with the GMD alone, the hybrid detector permits one to operate the GMD at considerably lower and safer voltages at given gains.

Figure 4.3: Gas gain for the GEM/GMD hybrid vs. ΔV_{gem} and V_c at 1 atm in Xe:CH₄. The gas gain from the GMD for each pressure was reproduced from D. Gobbi's thesis [24].

Figure 4.4: Gas gain for the GEM/GMD hybrid vs. ΔV_{gem} and V_c at 2 atm in Xe:CH₄. The gas gain from the GMD for each pressure was reproduced from D. Gobbi's thesis [24].

Figure 4.5: Gas gain for the GEM/GMD hybrid vs. ΔV_{gem} and V_c at 3 atm in Xe:CH₄. The gas gain from the GMD for each pressure was reproduced from D. Gobbi's thesis [24].

Figure 4.6: Gas gain for the GEM/GMD hybrid vs. ΔV_{gem} and V_c at 4 atm in Xe:CH₄. The gas gain from the GMD for each pressure was reproduced from D. Gobbi's thesis [24].

Figure 4.7: Gas gain for the GEM/GMD hybrid vs. ΔV_{gem} and V_c at 1 atm in Ar:CH₄. The gas gain from the GMD for each pressure was reproduced from D. Gobbi's thesis [24].

Figure 4.8: Detector gain vs. the conversion field at 4 atm in Xe:CH₄.

4.2.3.2 Detector Gain vs. Drift Voltage

Figure 4.8 shows the detector gain versus the conversion field at 4 atm with the GEM potentials and the GMD cathode voltage fixed. There is an increase of gain with the conversion field. Notice the electron loss when the conversion field is lower than 1.5 kV/cm.

4.3 Energy Spectra and Energy Resolution

The energy response of the hybrid detector can be measured either by the QPA02 pre-amplifiers and their amplifier board, or by the commercial pre-amplifier Ortec 142PC and amplifier Ortec 450. But the Ortec 142PC and 450 have better linearity and lower noise compared with QPA02, which was designed to provide a fast signal rather than to be used for spectroscopy. So the Ortec 142PC and 450 were used in the measurement of energy spectra from the radioactive sources and from x rays for the MTF measurement. The same pulse height analysis system as shown in Figure 3.8 was used. Some x-ray spectra collected by using the QPA02 are presented here too.

When collecting the x-ray spectra, the fan-beam slit and anti-scatter slit were in place. The fan-beam slit was removed to increase the photon fluence when collecting the spectra from the calibration sources, and the setup for the gain measurement shown in Figure 4.2 was used. Only the sensitive area on the GEM/GMD that is used for imaging was irradiated during the spectrum measurement. Some of the electrons produced near the boundary of the sensitive area will be lost. However, that gives the energy information used for the imaging. The reason that the full area of the detector is not used for the spectrum measurement is because the gain at different areas of the GEM and the GMD is not always the same.

For all the energy spectrum measurements, the Ortec 450 was set to positive unipolar output, 1 μ s shaping time, 25 ~ 50 gain. The central 16 anodes of the GMD were grouped together to collect the spectrum.

Figure 4.9: ^{55}Fe spectrum obtained with Ar:CH₄ at 1 atm.

4.3.1 Calibration Sources

Ar:CH₄

For the experiments with argon, ^{55}Fe was used as the calibration source. The absorbed energy spectrum from the GEM/GMD at 1 atm is shown in Figure 4.9. The full energy γ peak at 5.90 keV and the escape peak at 2.92 keV are shown in the spectrum. After the γ is absorbed in the argon, a 2.98 keV K fluorescence photon is produced for 10% of the time. When this fluorescence photon escapes from the active volume of our detector, the escape peak is obtained.

Xe:CH₄

^{241}Am spectra were measured for xenon gas. ^{241}Am produces several well-separated lines over the range of 14-60 keV. Table 4.2 gives the emission energies of ^{241}Am [48].

Figure 4.10: ^{241}Am spectrum obtained with $\text{Xe}:\text{CH}_4$ at 1 atm (0.11 keV per channel).

Figure 4.11: ^{241}Am spectrum obtained with $\text{Xe}:\text{CH}_4$ at 2 atm (0.09 keV per channel).

Figure 4.12: ^{241}Am spectrum obtained with Xe:CH_4 at 3 atm (0.13 keV per channel).

Figure 4.13: ^{241}Am spectrum obtained with Xe:CH_4 at 4 atm (0.15 keV per channel).

Table 4.2 Emission Energies (keV) and absolute intensities of ^{241}Am

Np x ray				γ ray	
L_I	L_α	L_β	L_γ		
11.9 (0.85%)	13.9 (13.3%)	17.7 (19.3%)	20.8 (4.93%)	26.3 (2.4%)	59.6 (35.7%)

Figure 4.10 to 4.13 show the spectra produced by ^{241}Am in xenon at 1-4 atm. The full-energy peaks at 13.8 keV, 17.7 keV and 59.6 keV are clearly seen. The two escape peaks K_α and K_β are produced after the Xe fluorescence photons K_α (~33.8 keV) and K_β (~29.7 keV) escape from the sensitive volume in the detector. The γ emission at 26.3 keV is hidden under the K_β escape peaks. The little peak between the 17.7 keV and K_β escape peak is the L escape peak, which is about 4.3 keV below its parent peak 26.3 keV. The peak at 7 ~ 8 keV might be the copper fluorescence photons K_α (8.03 keV) which are produced when the incident x-ray photons or the Xe fluorescence photons with energies above the copper K edge (8.98 keV) are absorbed in the copper layer of the GEM foil.

In the spectrum at 1 atm, the peak at 47 keV is due to the saturation of the Ortec 450. The gain of 450 was too high.

4.3.2 Energy Resolution

The energy resolution was measured under two conditions: Ar:CH₄ at 1 atm and Xe:CH₄ from 1 to 4 atm. The energy resolution was determined by measuring the full-width at half-maximum (FWHM) of the 5.9 keV ^{55}Fe peak for Ar:CH₄, and of the 17.7 and 59.6 keV ^{241}Am peaks for Xe:CH₄.

The computing method for calculating the FWHM of each peak from the obtained spectra is described as follows. First, locate a peak. Since the two peaks concerned in the ^{241}Am spectrum are resolvable, and the position of each peak, i.e. the energy of each peak E_0 , is known, this step is very straightforward. Second, the data in the local area of the peak are fitted with a Gaussian function. Third, the standard deviation σ of this Gaussian distribution is calculated. Then we can calculate the energy resolution by using Eq. (2.13).

When the effects of background continuum and peak tailing are significant, they have to be subtracted from the peak area. The data in the channels on either side of the peak are normally used to define the continuum, and an assumed linear curve is fitted to produce an estimated continuum in the region under the peak. Channel-by-channel subtraction of the continuum then produces corrected data for the subsequent Gaussian fit.

The energy resolutions of the hybrid detector in Ar:CH₄ at 1 atm, and in Xe:CH₄ at 1-4 atm are listed in Table 4.3. As shown in Table 4.3, the energy resolution varies from 1 to 4 atm in Xe:CH₄. It is mainly due to the variation of the operating condition of our detector. D. Gobbi [24] measured the energy resolution of the GMD in Xe:CH₄ at 1 atm to be 10.9% for 17.7 keV, which is about 1.6 times worse than these results with the GEM/GMD. The resolution for 5.90 keV in Ar:CH₄ (20%) obtained from our hybrid detector is a bit worse than D. Gobbi's result (18%). As mentioned in Chapter 2, the energy resolution is mainly affected by the variation of the gas gain. Since our detector was run at very low gain, the limiting energy resolution was not determined.

Table 4.3: Energy Resolution of the GEM/GMD hybrid for Ar (1 atm) and Xe (1-4 atm)

	5.9 keV	17.7 keV	59.6 keV
Ar:CH ₄ 1atm	20%	-	-
Xe:CH ₄ 1atm	-	7%	-
Xe:CH ₄ 2atm	-	9%	5%
Xe:CH ₄ 3atm	-	11%	10%
Xe:CH ₄ 4atm	-	10%	8%

4.3.3 Spectra Used for Spatial Resolution Measurement

Figure 4.14 to 4.16 are the energy spectra for x rays used for spatial resolution measurements and imaging at 2-4 atm. Each spectrum is normalized by area in order to compare them. All the spectra at each pressure were collected at the same time, and the MCA was calibrated with ²⁴¹Am. The average energies for these spectra at different pressures are listed in Table 4.4. More high-energy photons are absorbed in the detector.

Figure 4.14: Energy spectra for x rays used for spatial resolution measurement and imaging at 2 atm (0.09 keV per channel).

Figure 4.15: Energy spectra for x rays used for spatial resolution measurement and imaging at 3 atm (0.13 keV per channel).

Figure 4.16: Energy spectra for x rays used for spatial resolution measurement and imaging at 4 atm (0.15 keV per channel).

Figure 4.17: Energy spectrum shows the beam hardening effect by adding a 72.2 mm PMMA (polymethyl methacrylate) filtration to 50 kV at 4 atm (0.15 keV per channel).

when the pressure goes higher. So as shown in Table 4.4, the average energies for each x-ray tube voltage increase with the pressure.

Table 4.4 Average Energy (keV) deposited by x-ray beam in the GEM/GMD hybrid using Xe:CH₄ at 2-4 atm.

	2 atm	3 atm	4 atm
50 kV + 2.4 mm Al	15.6	18.1	19.8
40 kV + 1.7 mm Al	16.5	18.9	20.1
30 kV + 1.2 mm Al	15.7	17.6	18.3
20 kV + 0.5 mm Al	12.8	-	-
13 kV + 0.25 mm Be	9.56	10.1	10.0

For the spectra at 40 kV and 50 kV, all the escape peaks are superimposed and are hidden under the continuous bremsstrahlung spectrum, which is due to the broad continuous incident x-ray spectrum (the output of x-ray tube). So there are no escape peaks visible in the spectra even though almost all the K_α and K_β fluorescence photons escape from the detector.

The 8 keV peak that shows in the ²⁴¹Am spectra appears in all x-ray spectra (20 – 50 kV) except the 13 kV spectrum. From Figures 4.14 to 4.16, the area under this 8 keV peak decreases when the x-ray energy decreases. This is because there are less x-ray photons above the Cu K edge (8.98 keV) at lower tube voltage. The proportion of these x-ray photons gets so low at 13 kV that this 8 keV peak does not show in the 13 kV spectrum. It might be hidden under the bremsstrahlung spectrum. This peak did not show in the spectra collected by the GMD alone [24].

Figure 4.17 shows the beam hardened by adding 72.2 mm PMMA (polymethyl methacrylate) to 50 kV x ray at 4 atm. The portion of x-rays with energy higher than the xenon K-edge is increased by the extra filtration of PMMA.

4.3.4 Spectra measured with QPA02

The QPA02 preamplifiers were used for imaging. The absorbed energy information for those photons that generate valid signals in the detector during imaging can be

obtained when analyzing the raw imaging data. The software for image generation provides this option. Figure 4.18 gives an example of the cathode spectrum. It has lower resolution compared with spectra collected with Ortec 142 PC and 450 shown in Figure 4.14 to 4.17. The cathode spectrum could in principle be used to apply an energy window to the imaging data for interactive image display, or be used for dual energy imaging with one exposure.

Figure 4.19 shows the spectra collected from 16 anodes individually. These anode spectra are generated after the relative gain between the 16 anodes [24] are calibrated. Ideally we should get same spectrum from each anode, but due to the electron loss at the boundary of the detector's sensitive volume, the spectra collected on those anodes that are close to the boundary, i.e. anodes 1, 2 and 15, 16, are distorted.

Figure 4.18: A cathode spectrum obtained by QPA02.

Figure 4.19: Spectra from individual 16 anodes obtained by QPA02.

4.4 Spatial Resolution

The spatial resolution of the GEM/GMD hybrid is determined by the Modulation Transfer Function (MTF) measurement. The MTF characterizes how well the detector can transfer the contrast information at any spatial frequency. It is defined by [42]:

$$MTF(f) = \frac{M(f)}{M(0)} \quad , \quad (4-8)$$

where M , the modulation (contrast) of signal, is defined by:

$$M(f) = \frac{\psi_0}{\psi_{av}} = \frac{\psi_{max} - \psi_{min}}{\psi_{max} + \psi_{min}} \quad , \quad (4-9)$$

here ψ is the amplitude of the signal.

4.4.1 Modulation Transfer Function Measurement

The MTF of the detector is obtained by measuring the Line Spread Function (LSF) of the detector. There are two slits used for the LSF measurements. The first one is a lead slit with width of $40 \pm 5 \mu\text{m}$, and was used at x-ray energies from 30 to 50 kV. The second is a $23 \pm 3 \mu\text{m}$ wide steel slit. It was only used at 10 and 13 kV. During the measurement, the slit was mounted on the object stage with its orientation the same as that of the GMD strips.

The GEM hole and the GMD strip structure introduce spatial phase shift to the image obtained from the hybrid. In order to reduce this effect and ensure a consistent result, a standard procedure was applied to the LSF measurement:

First, for each LSF measurement, four slit acquisitions were taken $50 \mu\text{m}$ apart on the image plane. The time for each LSF measurement depends on the x-ray energy used.

Second, in the position space, the four LSF acquisitions are shifted to be coincident with each other, and then are summed and averaged. The average background was

subtracted, and all pixels outside of the LSF peak were set to zero.

Finally, a Fast Fourier Transform (FFT) is applied to the average LSF. Then the absolute value of the transform was taken, and the result was rescaled to 1 at zero to provide the MTF:

$$MTF(f) = \frac{|F\{LSF(x)\}|}{|F\{LSF(x)\}|_{f=0}}, \quad (4-10)$$

where $F\{\}$ denotes the Fourier Transform, f is the spatial frequency (usually in units of lp mm^{-1}). Everything after the first zero was set to zero for each MTF curve.

4.4.2 Results

The spatial resolution of the hybrid detector was measured in Ar:CH_4 at 1-2 atm, and in Xe:CH_4 at 1-4 atm. All quoted measurements reflect distances in the plane of the GMD (the same distances apply at the GEM foil, since those electrons amplified by the GEM are brought perpendicularly to the GMD by the collection field, although the x-ray beam itself is divergent). For the measurement in Xe:CH_4 at 2-4 atm, the potential across the GEM was increased as high as possible. The output signal was monitored by a digital scope to make sure the voltage across the GEM was not excessive. Once the GEM potential was fixed, the GMD cathode voltage was chosen according to the x-ray energy to maintain the cathode signal output from the amplifier board near its maximum of ~ 500 mV. For the measurement in Xe:CH_4 at 1 atm, both ΔV_{gem} and V_c were changed for each x-ray energy.

Table 4.5 Gas gains used for the MTF measurement and imaging

	Xe:CH_4				Ar:CH_4
	1 atm	2 atm	3 atm	4 atm	1 atm
13 kV + 0.25 mm Be	390.5	355.2	330.1	425.1	243.5
30 kV + 1.2 mm Al	210.3	210.2	150.8	165.9	-
40 kV + 1.7 mm Al	-	160.1	123.5	140.0	-
50 kV + 2.4 mm Al	161.3	130.6	113.0	134.6	-

The gas gains used for the MTF measurement and imaging are listed in Table 4.5 for reference.

4.4.2.1 Modulation Transfer Function

The MTF curves for the GEM/GMD hybrid detector are demonstrated in two different ways. In Figure 4.20 to 4.23, the curves are presented for increasing x-ray energies at each gas pressure. In Figure 4.24 to 4.27, the curves are demonstrated for increasing gas pressures at each x-ray energy.

When the x-ray energy is below the xenon K-edge (34.6 keV), x rays interact primarily in the L-shell (L-edge is 5.22 keV), producing L-shell photoelectrons. Their range increases with the incident x-ray energy, so the resolution of the detector decreases when the x-ray energy increases from 13 kV to 30 kV. Once the x-ray energy is over the xenon K-edge, K-shell photoelectrons are produced. Since they have shorter range than the L-shell photoelectrons, the resolution gets better at 40 kV and 50 kV than that at 30 kV. On the other hand, since there are more x-rays above the xenon K-edge when the x-ray tube voltage is 50 kV, the resolution at 40 kV is worse than that at 50 kV. But if the tube voltage could be increased further, the MTF curve would fall since the K-photoelectron range would increase with the energy.

The photoelectron's range is reduced by the increased gas density, so the resolution increases with the gas pressure. This is demonstrated in Figure 4.24 and 4.25 for 13 kV and 30 kV respectively. The resolution for 40 kV and 50 kV increases from 1 atm to 3 atm, but decreases from 3 atm to 4 atm (Figures 4.26, 4.27). The reason for this is that the mean energy of the photons absorbed by the detector increases as the pressure $\times$ depth product of the detector increases, so the range of the K photoelectrons increases.

Figure 4.28 shows the results at 13 kV of 1 atm, and 10 kV of 2 atm in Ar:CH₄, and 13 kV of 1 atm in Xe:CH₄. The K-edge of Ar is 3.20 keV, and the L-edge of Xe is 5.22 keV. So the K photoelectrons in Ar have higher energy than the L photoelectrons in Xe with the same incident x-ray energy, which results in longer range (Eq. (2-12)) and therefore the worse resolution in Ar.

Figure 4.20: MTF curves for increasing x-ray energies at 1 atm.

Figure 4.21: MTF curves for increasing x-ray energies at 2 atm.

Figure 4.22: MTF curves for increasing x-ray energies at 3 atm.

Figure 4.23: MTF curves for increasing x-ray energies at 4 atm.

Figure 4.24: MTF curves for increasing gas pressures at 13 kV.

Figure 4.25: MTF curves for increasing gas pressures at 30 kV.

Figure 4.26: MTF curves for increasing gas pressures at 40 kV.

Figure 4.27: MTF curves for increasing gas pressures at 50 kV.

Figure 4.28: MTF curves of 13 kV at 1 atm and 10 kV at 2 atm in Ar:CH_4 , and of 13 kV at 1 atm in Xe:CH_4 .

Figure 4.29: The spatial resolution is improved by adding 72.2 mm PMMA (polymethyl methacrylate) filtration.

Figure 4.29 demonstrates an improvement of the resolution when 72.2 mm PMMA (polymethyl methacrylate) is in the beam. This is because the proportion of x rays above the K edge increases after the soft part of the x-ray beam is filtered out by the PMMA.

Table 4.6 lists the spatial frequency, f , at which $MTF(f)$ crosses 0.05 for each measurement. Those numbers quoted in brackets in the table are the results from the GMD alone. Compared with the spatial resolution obtained from the GMD alone [24], the resolution increases for almost all the measurements, as shown in the Table 4.6. One possible reason is that, with the gas gain from the GEM, the GMD is operated with much lower voltage, so the noise in the channel signals used to calculate the event centroid is lower. Additionally, the readout electronics were improved.

Figure 4.30 shows the effect of the energy window on the spatial resolution, which is an intriguing advantage of the photon-counting radiography.

Table 4.6 Spatial frequency (lp mm^{-1}) at which $MTF(f)$ crosses 0.05 (the numbers quoted in the brackets are the results from the GMD imager [24])

	Xe:CH ₄				Ar:CH ₄	
	1 atm	2 atm	3 atm	4 atm	1 atm	2 atm
10 kV + 0.25 mm Be	-	-	-	-	-	6.6 (7.0)
13 kV + 0.25 mm Be	9.0	12.7	16.9 (13.0)	17.8 (14.0)	4.0	-
30 kV + 1.2 mm Al	3.1 (3.1)	4.4 (3.8)	5.0 (5.4)	7.0 (6.2)	-	-
40 kV + 1.7 mm Al	-	6.6	11.3	8.1	-	-
50 kV + 2.4 mm Al	6.0 (5.5)	8.1 (6.7)	11.0 (8.4)	11.9 (7.0)	-	-

Figure 4.30: The effect of the energy window on the spatial resolution.

Figure 4.31: The parallel bar pattern and the star pattern.

4.4.2.2 Test Pattern Images

There are two test patterns that were imaged: one parallel bar pattern and one star pattern (see Figure 4.31). When the bar pattern was used, one set of three bars was placed in the field of view of the detector, and 0.5 – 1.0 mm of the pattern was scanned in 100 μm steps.

For the star pattern, each of the wedges provides a range of line densities. About 2–3 mm of one of the wedges was scanned. The line density in the image can be determined by the following method. The angle and radius of one wedge were measured, and the number of lines was counted, then the line density in the object plane at one location is equal to the number of lines divided by the arc length.

Bar pattern and star pattern images were obtained in Xe:CH_4 for some of the x-ray spectra and gas pressures at which MTF curves were measured. Figure 4.32 shows three bar pattern images and one star pattern image. The lp mm^{-1} values given in the images are those in the image plane. The two numbers shown to the right of each image represent the maximum and minimum pixel values in the presented image, which correspond to the white and black respectively in the image.

Figure 4.32 (a) is the bar pattern image for 13 kV at 2 atm. Figure 4.32 (b) is the image for 50 kV at 2 atm. Figure 4.32 (c) is for 50 kV at 3 atm.

The star pattern image was obtained for 13 kV at 3 atm (Figure 4.32 (d)). The spatial frequency at the top end of the image is 11 lp mm^{-1} , and it is 7.5 lp mm^{-1} at the bottom end. All the lines are clearly resolvable including 11 lp mm^{-1} . The line to the very left of the pattern does not extend to the top end. It was found scratched when examined under the microscope. Part of the first two rows in the image shows some pattern, where it was found that the lead layer on the star pattern was damaged. There is no severe artifact present in these test pattern images.

4.5 Images of Biological Specimen

A fish spine and a rat phalange were imaged with our hybrid detector filled with Xe:CH_4 . The fish spine was obtained for 13 kV at 3 atm (Figure 4.33). The rat phalange

Figure 4.32: The test pattern images (pixel size is 25 μm).

was obtained for 30 kV at 4 atm (Figure 4.34). As in the test pattern images, the two numbers shown to the right of each image represent the maximum and minimum pixel values and correspond to the white and black respectively in the image. These specimens were chosen because: first, they have both soft tissue and bone that have different attenuation coefficients for x rays; second, both the fish spine and the joint of the rat phalange have fine structures. In this way, the good contrast sensitivity and spatial resolution of our hybrid detector can be shown.

As mentioned in Chapter 1, the primary advantage of the digital radiography is the level and window interactive display. For a given gray scale, by changing the window width and the level (the center of the window) on the input intensity, the contrast sensitivity is changed and different information from one exposure can be extracted. In Figure 4.33 and 4.34, the concept of windowing and level is demonstrated. The window width and level in this case are all in term of pixel value, i.e. the number of photons hits at one pixel.

Figure 4.33 (a) shows the fish image with the full range of the pixel values [0, 214] that is presented in the image data. The window width is 214 and the level is 107. In Figure 4.33 (b) the window width is 84 and level is 92. We can see the fish spine structure, the different bone density at the different part of the spine, and some tissue attached to the spine. When the window width is changed to 44 and the level changed to 82 in Figure 4.33 (c), we can only see the structure of the fish spine. In Figure 4.33 (d), with the window width 134 and the level 67, both the spine structure and the tissue are shown but the contrast is lower compared with Figure 4.33 (b).

Figure 4.34 shows the effect of the application of different window width and level on the rat phalange image. Figure 4.34 (a) is the image obtained by using the full range of the pixel values [1069, 3655] from the image data. The minimum value is not zero, since there are always x rays transmitted through the object. The window width is 2586 and the level is 2362. In Figure 4.34 (b), we can see the three parts of the rat phalange: distal, middle and proximal phalange (from top to bottom), the two joints and the smooth development of the bone density in the phalange with the window width of 1086 and the level of 1612. After the window width is changed to 856 and the level is changed to 2097 in Figure 4.34 (c), we can see clearly the shadow of the thin skin on the phalange, but the

bone structure is not visible. In Figure 4.34 (d), the window width and the level are changed to 1456 and 1797 respectively. We can see the three parts of the rat phalange, the phalange joint structure, the smooth development of the bone density in the phalange, and the shadow of the thin skin of the phalange.

In Figure 4.34, between the nail and the first piece of phalange bone, there are two rows sharply bright, i.e. the gradient is quite big between the dark part and bright part. It looks like an artifact, which might be due to the line-to-line corrections applied in the image analysis program, the pixel efficiency correction and the dead-time correction.

Figure 4.33: Fish spine image (13 kV at 3 atm, pixel size is 25 μm).

Figure 4.34: Rat phalange image (30 kV at 4 atm, pixel size is 25 μm).

Chapter 5

Conclusions and Future Work

This chapter summarizes all the experimental results and the operation of the GEM. Some options for future work, including short term and long term, and the applications of the system are discussed.

5.1 Conclusions

The presence of the GEM leads to a decrease of the GMD voltage of more than 100 V for the same resulting gain, allowing a much safer operating mode for the GMD.

Recall that the GEM gain is not only determined by the field in the hole but is also affected by the outside fields, i.e. the conversion field and the collection field. When the cathode voltage of the GMD is increased to get further amplification, the collection field strength is reduced, which results in a decrease of the collection efficiency when working with a low collection field. In our system, the GEM voltage is applied with a resistor network. The voltage at the GEM bottom is limited by the potential across the GEM.

The gain of the GEM/GMD hybrid was less than 400 for the MTF measurement and imaging. The gain was chosen to maintain a maximum output signal from the amplifier board (~ 500 mV).

The energy resolution varies from 1 atm to 4 atm, which is due to the different operating condition of our detector at the different pressures. The highest energy resolution is obtained at 1 atm, 7% for 17.7 keV, and the worst resolution is 11% for 17.7 keV at 3 atm. At 59.6 keV, the resolution is 5% at 2 atm and 10% at 3 atm. Compared

with the GMD imager [24], the energy resolution is improved from 10.9% to 7% for Xe:CH₄ at 1 atm.

Compared with the results from the GMD imager at 4 atm [24], the spatial resolution of our hybrid detector increases from 14.0 lp mm⁻¹ to 17.8 lp mm⁻¹ for 13 kV; the resolution for 30 kV increases from 6.2 lp mm⁻¹ to 7.0 lp mm⁻¹; for 50 kV, it increases from 7.0 lp mm⁻¹ to 11.9 lp mm⁻¹.

As a conclusion, the GEM/GMD hybrid detector is suitable for high pressure digital radiography. The whole system is more robust than the GMD alone. The spatial resolution is not degraded by the GEM hole structure. The image quality looks better than that obtained with the GMD imager. There are fewer artifacts present in the obtained images.

5.2 Summary of the Operational Features of the GEM

5.2.1 Advantages

Increase of the primary charge

The nice feature of the GEM is that it can be used as a pre-amplifier and it amplifies the primary electrons inside the detector. This property distinguishes the GEM from other gas detectors. From the point of view of the GMD strips, the primary charge increases. Owing to the larger primary charge, the GMD gain, and thus the anode-cathode voltage, can be lowered, which reduces the risk on the occurrence of discharges.

Operation at higher gas pressure

With the GEM as a pre-amplifier, the GMD gain needs not to be turned up to the maximum. If we get an effective gain of 100 from the GEM and of 5 from the GMD, a combined effective gain would be on the order of 500. In pressurized gases, where the

single GMD gain is drastically reduced, the addition of the GEM extends the maximum usable gas pressure, improving the x-ray detection efficiency and position resolution.

5.2.2 Disadvantages

High voltage application

The use of a GEM in a GMD necessitates two more high voltage (GEM top and bottom) connections to the detector. Considerably high voltages have to be applied to the electrode planes to achieve high charge collection efficiency. For our experiments at 4 atm, the voltage on the drift plane was -2.8 kV, the GEM top -2.1 kV and the bottom -1.2 kV. Since the conversion and collection gap are 3.9 and 1.8 mm respectively, application of these high voltages demands special attention in the design of the detector to prevent discharge.

Monolithic character of the GEM

The fact that the GEM is a monolithic device, meaning that breakdown at a single spot renders the complete device useless, is a weak point. The yield and quality control of the current GEM production is however high enough to ensure good operation.

5.3 Suggestions for the Short Term Future

Continue testing the performance of the GEM/GMD

Although the current GMD print showed spontaneous discharge signals (7 ~ 10 counts/min) during the experiments at 4 atm, it is probably able to survive 5 atm with less intensive irradiation. It would be interesting to examine the spatial resolution of the hybrid detector for 40 kV and 50 kV x rays at 5 atm. Before increasing pressure, it would be useful to obtain the test pattern images at 4 atm.

Remove the dead xenon layer

There are 3.5 mm of dead xenon in front of the detector (between the window and the drift plane), which is due to the thickness of the drift plane frame. The easier way to eliminate it is to turn over the drift plane frame, with the Mylar sheet touching the vessel window. Then turn over the Mylar sheet, since only one side of the Mylar sheet is aluminized, and the aluminized side must face the GEM to form the conversion field.

If the next step would be to go to the keystone geometry directly, this advice could be ignored since the orientation of the Mylar sheet would not matter.

Install the PCB readout board for the GEM

The GEM can be used as an independent detector, and signals can be read out by a simple printed circuit board with passive pickup electrodes, i.e. there is no high voltage at the readout element, so there is no further amplification after the GEM foil.

In this mode of operation, after the primary electrons released in the conversion gap are guided to the GEM holes and amplified in the avalanche, they will exit the holes and follow the field lines to the readout board, and part of them will be trapped by the GEM bottom electrode. Meantime, the ions produced in the conversion gap and in the GEM holes will be collected by the drift plane and the GEM top electrode. Since the signal is entirely produced by electrons and no ions are produced in the last gap, this operation mode is intrinsically fast and safe. The moderate field in the collection region prevents the propagation of a discharge in the GEM to the readout strips [29]. This is a rare but always possible event. So the possibility of damaging the amplifiers is reduced when the signal from the GEM is picked up by a PCB readout element.

With the advanced technologies in PCB design and manufacture, a cheap large area detector could be made. And the readout circuit could be patterned in any desired geometry (strips, rings, pads, ...) depending on the application. Non-planar, cylindrical geometries are possible.

We have a readout board with parallel passive strips at hand. The width of each strip is 150 μm , and the pitch is 200 μm . It was designed by J. Dubeau (an Associate

Researcher in the Dept. of Physics) and made at CERN. The PCB readout board can be installed to replace the GMD in the pressure vessel, with maintaining the current geometry. The physical performance of the GEM with the PCB readout element can be tested and thus understood.

In the setup of the GEM + PCB, the signal from the GEM top or bottom could be used as the trigger signal. Since the fraction of the electrons trapped by the GEM bottom is dependent on the ratio of the collection field and the field in the GEM holes, there will be a tradeoff between the collection efficiency and the size of the trigger signal. But the top electrode does not have this problem.

On the other hand, experiments conducted by M. Dixit and J. Dubeau [49] showed that there was a distribution of the induced charge signal on the neighboring strips when a collimated α source was used to irradiate only one strip on the PCB readout element (referred to as the central strip). This is due to the change in the electrostatic potential energy of the system caused by the motion of electrons drifting in the collection gap in the detector. The PCB readout board used in their experiment had 1.65 mm pitch and 0.15 mm gap between the readout strips. The collection gap was 2.5 mm. The ratio of signal amplitude at the first neighboring strip to that at the central strip was found to be dependent on the type of amplifier and the shaping time used. The effect of the neighboring induced signal on the centroid calculation should be examined for our imaging system.

Update the computer

It would be nice if the 80386 PC could be updated. Since the data acquisition is done by software, the slow clock speed of the computer (40 MHz) limits the event count rate of the imaging system. The dead time of the system is quite high due to the slow speed of the PC and the CAMAC interface software. The dead time was about 80% when doing a blank field scan. The typical data rates were 100-300 events/s. In order to get sufficient photon statistics, a long imaging scan time is required. The rat image presented in this thesis took two days to obtain.

5.4 Some Options for the Long Term Future

The simplicity, ruggedness and low cost of the GEM device plus the available advanced fabrication technologies provide many options for the GEM applications.

Figure 5.1: Orientation of the keystone GEM detector.

Keystone geometry

Our current geometry of the detector provides very low quantum efficiency ($< 10\%$ at 30 kV [24]), which is mainly due to the short conversion gap (4 mm). One way to increase the quantum efficiency significantly without introducing parallax error is to use the “keystone” geometry, i.e. the readout strips follow the divergence of the x-ray beam, in which case, the absorption length will be equal to the total length of the sensitive area of the GEM (70 mm), or the readout board which might be a bit shorter than the GEM.

After trying the GEM with PCB readout board as discussed in previous section, we could go to the “keystone” geometry. The concept of a SPR system with the keystone GEM detector is shown in Figure 5.1. Compared with the GMD, it would be much easier and cheaper to realize the keystone geometry with the GEM and its PCB readout element. Due to the unique operation mode, it would solve the charging-up problem showed in the experiments conducted by Kiourkos et. Al [50] with Microstrip Gas Chambers (MSGCs) (the same structure as the GMD) of keystone electrode geometry.

One disadvantage of the GEM detector with keystone geometry is that it is still a one-dimensional detector, so it can only be used via SPR system to get a two-dimensional image.

Cascaded GEM

If the gain from a single GEM is not high enough for imaging, two or three GEM meshes could be cascaded together, which is called Double GEM or Triple GEM. In this way the operation on each GEM mesh is much safer, like the case in the GEM/GMD hybrid.

For the Double GEM, the gap between the two GEMs is named the transfer region (the collection field for the first GEM), and the first GEM serves as an electron injector for the second one. The overall gain is the product of the effective gains of the two elements.

The charge amplification and transfer processes in the Double GEM have been investigated by Bachmann et. al [33]. Their experiments showed that the two multipliers operated essentially independently, although the transfer field for the first GEM is the drift field for the second, therefore constraining the operation. Recall that the collection field for each GEM has to be much higher than its conversion (drift) field to get a high electron collection efficiency. However, it was shown that the effective gain of a double GEM detector was almost invariant from the sharing of the multiplying voltage between the two GEMs, provided that their sum was constant. Meanwhile, the alignment between the holes on the two GEM meshes were not important, and the electron diffusion was large enough to obliterate the hole structure.

Two-dimensional GEM detector

As mentioned in chapter 1, one of the drawbacks for the SPR system is the high x-ray tube heat loading. Two dimensional readout electrodes for the GEM would dramatically reduce the tube loading.

A two-dimensional GEM detector was built by A. Bressan et al. [51] The induced charge signal on sets of adjacent strips were read out with gated ADCs. The signal picked up through a HV capacitor from the lower GEM electrode was used as the trigger for the system. An image of the foot of a bat was obtained with 8 keV x rays, and showed the foot profile but not the joint structure.

The method of manufacturing two-dimensional pick-up electrodes is extended from the principle of the GEM detector [52]. Two orthogonal sets of parallel metal strips are engraved, using conventional printed circuit technology, on the two sides of a thin polymer (Kapton) foil. After gluing the foil on a thin insulating support frame, the polymer in the interstices between the upper strips is removed with a solvent, enabling the bottom layer to collect part of the electron charge. In the electron collection mode, both read-out electrodes can be kept at ground potential, which is a substantial advantage as compared to other two-dimensional devices.

Since the keystone geometry cannot be used with the two-dimensional readout element, the same low quantum efficiency problem as in our current detector remains.

GEM + TFT readout

As mentioned in Chapter 1, large active readout matrices consisting of Thin-Film Transistor (TFT) arrays are employed in the current commercial digital radiography systems, e.g. the Se detector. We could take advantage of this well-developed technology to build a large area two dimensional GEM detector. However, it would have the same problem — low quantum efficiency due to the short absorption depth.

5.5 Applications

With the current available technologies, we could build a bench-top SPR GEM system, with a simple PCB readout and keystone geometry. The channel number could be increased to enlarge the active area of the detector. This system could be used as a research tool to examine biological specimens or the quality of some tiny ICs.

At some point in the future, we could build a quantitative CT system with GEM + PCB. The quantum efficiency would not be a problem by applying the keystone geometry. Such a system could find more applications in the medical and industrial areas. The readout electronics that we are using now are only for investigating the physical performance of the novel detector. They would have to be updated for the specific application.

As another option, we could build a two-dimensional GEM detector with the same geometry that is applied in our current system. TFT arrays could be applied to the readout electrode to obtain small pixel size. In order to reduce the parallax error, both the GEM foil and the readout electrode could be built on the surface of a sphere centered on the focal spot of the x-ray tube. Since there is a limit on the quantum efficiency, this detector would be for applications in the industrial or in the research lab, where the dose is not a concern.

Appendix A

Modeling the GEM/GMD Hybrid detector

The centroid calculation algorithm applied in the GMD imager did not work properly in the hybrid detector at the beginning. There was a large bias toward the anodes. It was thought to be due to the GEM hole structure. So investigating the effect of the GEM hole structure on the centroid calculation was the initial motivation to simulate the signal development in the hybrid detector. Later on, a minor bug was found in the Weighted Centroid Method coded in the program *image.for* (a factor of two was missed).

This simple simulation is operated in two dimensions, where the x direction is along the GMD readout direction, and the incident direction of photons is the z direction. For each incident photon, it is assumed that it enters the detector perpendicularly and the incident position (x_i) follows a uniform distribution along the x direction. Then it attenuates exponentially along the z direction, so the z coordinate of the photon interaction z_i is a random number generated from an exponential distribution. For each photon interaction, it is assumed that the charge cloud (initial ion pairs) is produced isotropically around the interaction point (x_i, z_i) , and the centroid of the charge cloud is at the location where the photoelectron effect happens. Then electrons generated in the photoelectric effect drift toward the GEM mesh in the uniform electric field between the drift plane and the GEM top. Due to the lateral diffusion, these electrons generate a Gaussian distribution with a mean value x_i and width σ_1 :

$$P_1(x) = \frac{1}{\sqrt{2\pi}\sigma_1} \exp\left(-\frac{(x-x_i)^2}{2\sigma_1^2}\right) . \quad (\text{A-1})$$

The width σ_1 is given by (as for Eq. 2.10):

$$\sigma_1 = \sigma(1 \text{ cm})\sqrt{z} \quad . \quad (\text{A-2})$$

where z ($= 0.4 \text{ cm} - z_i$) is the drift distance of the electrons. $\sigma(1 \text{ cm})$ [53] is the lateral diffusion of electrons after 1 cm of drift.

The transparency of the GEM is assumed to be $T_1 = 1$. The Gaussian distributed primary charge is then integrated over the GEM pitch [$x_h - 70 \mu\text{m}$, $x_h + 70 \mu\text{m}$] (x_h is the location of one GEM hole) to obtained a simulated charge Q_h that goes through each GEM hole:

$$Q_h = T_1 \int_{(x_h - 70 \mu\text{m})}^{(x_h + 70 \mu\text{m})} P_1(x) dx \quad . \quad (\text{A-3})$$

Assume the GEM has uniform gain M_{gem} over each hole, then the charge after each hole is: $Q_h M_{\text{gem}}$. It is assumed that when these electrons drift toward the GMD anodes, their lateral diffusion follows a Gaussian of mean value x_h and width σ_2 :

$$P_2(x) = \frac{1}{\sqrt{2\pi}\sigma_2} \exp\left(-\frac{(x - x_h)^2}{2\sigma_2^2}\right) \quad . \quad (\text{A-4})$$

where, x_h is the position of each GEM hole center, σ_2 is determined by Eq. (A-2) and the drift distance of these electrons is determined by the collection gap.

The Gaussian distributions described by Eq. (A-4) are integrated individually over the GMD anode pitch [$x_a - 100 \mu\text{m}$, $x_a + 100 \mu\text{m}$]. The charge signal for each anode is the sum of the contribution from each Gaussian:

$$Q_u = \sum_h \int_{x_a - 100 \mu\text{m}}^{x_a + 100 \mu\text{m}} \frac{1}{\sqrt{2\pi}\sigma_2} \exp\left(-\frac{(x - x_h)^2}{2\sigma_2^2}\right) \quad . \quad (\text{A-5})$$

where $(x_h - 2\sigma_z) \leq x \leq (x_h + 2\sigma_z)$.

It is assumed that the collection efficiency (see section 2.2.5) of the detector is $T_2 = 1$, and the GMD gain (M_{gmd}) is uniform over each anode. So the simulated charge signal collected by each anode is: $M_{gmd} T_2 Q_a$.

The charge distribution over the sixteen anodes of the GMD in the hybrid detector at 1 atm in xenon for x rays with average energy 15 keV was simulated. Figures A.1 and A.2 give two examples of the simulation geometries. In the geometry shown in Figure A.1, the centroid of the charge cloud is at GMD anode 8. At the beginning, there is one GEM hole aligned with GMD anode 8 and thus with the charge cloud centroid. Then the GEM is moved toward the GMD anode 16 along the GMD readout direction. The GEM hole that is aligned with anode 8 at the beginning is now 100 μm to the right of anode 8. The charge distributions over the sixteen anodes of the GMD for the two GEM positions are shown in Figure A.3 (a) and (b) respectively. We can see that the charge distribution shown in Figure A.3 (b) is not as symmetrical as that shown in Figure A.3 (a), which introduces the bias of $0.4 \pm 0.1 \mu\text{m}$ in the calculated centroid that is shown in Figure 2.4.

For the geometry shown in Figure A.2, the centroid of the charge cloud is over GMD cathode 7. There is one GEM hole aligned with this cathode at the beginning, and then this GEM hole is moved 80 μm to the right of the cathode 7. The charge distributions for these two GEM positions are shown in Figure A.4 (a) and (b). Similarly, after the GEM is moved, unsymmetrical charge distribution is shown (Figure A.4 (b)).

Figure A.1: Diagram of one geometry for the charge distribution simulation. The centroid of the charge cloud is at GMD anode 8. At the initial position of the GEM, there is one GEM hole aligned with GMD anode 8.

Figure A.2: Diagram of one geometry for the charge distribution simulation. The centroid of the charge cloud is at GMD cathode 7. At the initial position of the GEM, there is one GEM hole aligned with GMD cathode 7.

(a)

(b)

Figure A.3: Simulated charge distribution over the 16 anodes of the GMD in the GEM/GMD hybrid detector. The charge cloud centroid is at the GMD anode 8: (a) a GEM hole is aligned with GMD anode 8; (b) the GEM hole is 100 μm to the right of anode 8.

(a)

(b)

Figure A.4: Simulated charge distribution over the 16 anodes of the GMD in the GEM/GMD hybrid detector. The charge cloud centroid is aligned with GMD cathode 7: (a) a GEM hole is aligned with the cathode 7; (b) the GEM hole is 80 μm to the right of the cathode 7.

Appendix B

Gas Gain Fluctuation

Gas multiplication is a stochastic process. The single-electron avalanche distribution in a uniform electric field can be described by the Furry distribution [38], which states that if $\bar{A}$ is the average gain, the probability of having a gain A in a single avalanche obeys:

$$P(A) = \frac{1}{\bar{A}} \left(1 - \frac{1}{\bar{A}}\right)^{A-1} . \quad (\text{B-1})$$

This expression holds under the condition that the probability of ionization is independent of its previous history, but dependent only on the electric field strength. When $\bar{A}$ is reasonably large (greater than 50 or 100), the Furry distribution reduces to a simple exponential form:

$$P(A) \approx \frac{1}{\bar{A}} \exp(-A/\bar{A}) . \quad (\text{B-2})$$

In strong electric fields, like ones in the GEM and GMD, the probability of ionization by an electron can no longer be considered totally independent of its past history. The simple exponential distribution of Eq. (B-2) is replaced by a Polya distribution [38]:

$$P(A) = \left(\frac{A}{b\bar{A}} \right)^{\frac{1}{b}-1} \exp\left(-\frac{1}{b} (A/\bar{A}) \right) . \quad (\text{B-3})$$

So the single-electron avalanche distribution in the GEM and GMD can be described by Eq. (B-3). The relative variance predicted by the Polya distribution is:

$$\left(\frac{\sigma_A}{\bar{A}} \right)^2 = \frac{1}{\bar{A}} + b . \quad (\text{B-4})$$

For large values of the multiplication factor $\bar{A}$.

$$\left(\frac{\sigma_A}{\bar{A}} \right)^2 \approx b . \quad (\text{B-5})$$

The width of the gain distribution in proportional counters is mainly determined by the weaker field at the beginning of the avalanche. Consequently, a sharp transition from drift to avalanche region like in the GMD is favorable for the energy resolution.

The average gain $\bar{A}$ is what we usually call the detector gain M:

$$M = \bar{A} = \frac{1}{n_0} \sum_{i=1}^{n_0} A_i . \quad (\text{B-6})$$

where n_0 is the initial number of ion pairs created by the incident x-ray. Because each avalanche is assumed to be independent, we can apply the error propagation formula to (B-6) to obtain:

$$\sigma_M^2 = \frac{1}{n_0} \sigma_A^2 . \quad (\text{B-7})$$

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