INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

A High-Pressure Gas Microstrip Detector for Digital Radiography

by

David G. Gobbi

B.Sc. (University of British Columbia) 1995

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

Department of Physics
Carleton University
Ottawa-Carleton Institute for Physics
Ottawa, Ontario, Canada

August 20, 1997

© copyright

1997, David G. Gobbi

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-27049-1

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

A High-Pressure Gas Microstrip Detector for Digital Radiography

submitted by

David G. Gobbi

B.Sc. (University of British Columbia) 1995

in partial fulfilment of the requirements
for the degree of Master of Science

Chair, Department of Physics

Thesis Supervisor

Thesis Supervisor

Carleton University

Date 16th Sept '97

Abstract

The gas microstrip detector (GMD) is a miniaturized array of proportional counters printed onto a substrate. A benchtop photon-counting scanned-projection radiography system was used to evaluate the potential of the GMD for medical imaging.

Each photon event produces signals on several detector elements. The centroid of the signals provides an RMS resolution of $46\text{ }\mu\text{m}$ at 13 kV_p , which is less than one quarter the $200\text{ }\mu\text{m}$ detector pitch.

The modulation transfer function was measured at 1–4 atm for 10–50 kV_p x rays, and the RMS spatial resolution was compared to a radiation physics model. The limiting spatial resolution at 4 atm was $>6.5\text{ lp mm}^{-1}$ at 30 kV_p and $>8.2\text{ lp mm}^{-1}$ at 50 kV_p . The space-charge limited counting rate for unfiltered 30 kV_p x rays was $>2\times 10^6\text{ mm}^{-2}\text{s}^{-1}$ at 3 atm and $>3\times 10^7\text{ mm}^{-2}\text{s}^{-1}$ at 1 atm. Hence the rate capability extends into the range of medical imaging fluence rates. The energy resolution was 10.9% at 17.7 keV and 5.2% at 59.6 keV.

Acknowledgements

I would like to thank my supervisors, Paul Johns and Madhu Dixit, for providing the support to make this possible. Paul Johns for his excellent teaching and reliable criticism, and Madhu for sharing his knowledge, his ideas, and his enthusiasm. I would also like to thank the rest of the GMD imaging group, John Armitage, Dean Karlen, and Gerald Oakham. And Jacques Dubeau especially, for knowing where everything in the lab was and where to get it if it wasn't.

The technical support provided by Phillippe Gravelle, Ernie Neuheimer, and Morley O'Neill at the CRPP was invaluable. And special thanks to Jim Sliwka, the technical supervisor with the Physics Department, for giving me access to his machine shop and plenty of helpful suggestions.

Jim Carleton, Bill Jack, and Wade Hong provided an invaluable service by keeping the PC and UNIX networks up and running. And thanks to Gary Findlay, the electronics technologist in the department, for rescuing my terminal from an untimely death.

The major part of the funding for this research was provided by the Centre for Research in Particle Physics (CRPP) and the Faculty of Graduate Studies and Research at Carleton University. Natural Science and Engineering Research Council (NSERC) grant funds were used for supplementary expenses.

Contents

Acceptance sheet	ii
Abstract	iii
Acknowledgements	iv
List of Abbreviations	ix
List of Tables	xi
List of Figures	xii
1 Introduction	1
1.1 Digital Radiography	1
1.1.1 Conventional Radiography	2
1.1.2 Motivations for Digital Radiography	2
1.2 Comparison of Digital Radiography Methods	4
1.2.1 Digital Fluoroscopy	4
1.2.2 Computed Radiography	4
1.2.3 Screen/Photoreceptor Systems	4
1.2.4 Direct Conversion Systems	5
1.3 Scanned Projection Radiography	7
1.3.1 Slot Scanning	8
1.3.2 Slit Scanning	9
1.4 Imaging with Gas Avalanche Counters	9
1.4.1 Multiwire Proportional Counter	9
1.4.2 The Gas Microstrip Detector	11
1.4.3 Micro-Gap Counter	11
1.4.4 Microdot Chamber	12
1.5 Silicon Strip Detectors	12
1.6 Gas Microstrip Detector Imaging at Carleton University	13
1.7 Thesis Overview	14

2	Theory	15
2.1	Principles of GMD Operation	15
2.1.1	Signal Development	15
2.1.2	Detector Efficiency	17
2.1.3	Spatial Resolution	20
2.1.4	Energy Resolution	21
2.2	X-Ray Absorption in Xenon	22
2.2.1	X-Ray Interactions	22
2.2.2	Relaxation Cascade	24
2.2.3	Electron and Fluorescence Photon Ranges	26
2.3	Spatial Resolution of a Xenon Detector	29
2.4	Drift, Diffusion, and Multiplication of Charge	31
2.4.1	Electron Drift and Diffusion	31
2.4.2	The Gas Avalanche	33
2.4.3	Ion Drift	34
2.5	Charge Centroid Measurements	35
2.5.1	Discrete Centroid Integration	36
2.5.2	Effect of Charge Diffusion	36
2.5.3	Errors Arising in the Centroid Calculation	38
3	Imaging System	43
3.1	GMD-SPR Apparatus	43
3.1.1	50 kV X-Ray Tube and Power Supply	44
3.1.2	Fan-Beam Slit	45
3.1.3	Object Stage	45
3.1.4	LSF Slit	45
3.1.5	Anti-Scatter Slit	46
3.1.6	Pressure Vessel	46
3.2	Gas Microstrip Detector	46
3.2.1	GMD Construction	46
3.2.2	Electronics	49
3.2.3	Fill Gas	52
3.3	Readout Electronics	52
3.3.1	Amplifiers	54
3.3.2	Imaging Electronics	55
3.3.3	Spectroscopy Electronics	58
3.4	X-Ray Shielding	58
4	Image Generation	61
4.1	Software Overview	61
4.1.1	Data Acquisition	63
4.1.2	System Calibration	63

4.1.3	Image Generation	64
4.1.4	Image Display	64
4.2	Calibration Procedure	64
4.2.1	Anode Channel Calibration	64
4.2.2	Pixel Efficiency Calibration	68
4.3	Live Time Correction	70
4.4	Centroid Calculation	71
4.4.1	Weighted Centroid Methods	71
4.4.2	Comparison of Methods	74
4.5	Event Rejection	74
4.5.1	Event Rejection Criteria	75
5	Experimental Methods	78
5.1	Spatial Resolution Measurements	78
5.1.1	Criteria for Accurate Resolution Measurements	78
5.1.2	Modulation Transfer Function Measurements	79
5.1.3	Resolution Test Patterns	80
5.2	Energy Spectroscopy	82
5.2.1	EG&G ORTEC 142PC	82
5.2.2	QPA02	82
5.2.3	Pinhole Spectra vs. Slit Spectra	83
5.2.4	Energy Resolution Measurements	83
5.3	Gain Measurements	84
5.3.1	Relative and Semi-Absolute Gain	84
5.3.2	Absolute Gain	85
5.4	Rate Tests	86
5.4.1	Detector Current Method	86
5.4.2	Peak Method	87
6	Experimental Results	89
6.1	Spatial Resolution	89
6.1.1	MTF Measurements	89
6.1.2	Test Pattern Images	94
6.1.3	Comparison to Theory	98
6.2	Detector Gain	102
6.2.1	Gain Variation with Pressure	102
6.2.2	Gain vs. Drift Voltage	104
6.3	Counting Rate Ability	104
6.3.1	Gain via Detector Current	105
6.3.2	Gain via Multi-Channel Analyzer	106
6.3.3	Data at 4 Atm	108
6.3.4	Limiting Exposure Rate	109

6.4	Energy Spectra and Energy Resolution	110
6.4.1	Calibration Sources	111
6.4.2	Energy Resolution	114
6.4.3	Spectra Used for Spatial Resolution Measurements	114
6.5	Images	119
6.5.1	Early Images: Circuit Components	119
6.5.2	Later Images	123
7	Discussion and Conclusions	128
7.1	Summary and Discussion of Results	128
7.1.1	Spatial Resolution	128
7.1.2	Limiting Counting Rate	130
7.1.3	Detective Quantum Efficiency	130
7.1.4	Image Quality	131
7.1.5	Energy Resolution	131
7.2	Deterioration of the GMD with Age	132
7.3	Conclusions	133
7.4	Future Work	134
7.4.1	Recommended Modifications to the System	134
7.4.2	Increase of Detector Pressure	134
7.4.3	Keystone Geometry	135
7.4.4	Benchtop Computed Tomography	137
7.4.5	Dual Energy Radiography	138
7.4.6	Improvements to the Data Readout	138
7.4.7	Ultimate Goals	139
A	Atomic Physics of Xenon	140
A.1	Binding Energies and Vacancy Probabilities	140
A.2	Relaxation Cascade	140
A.2.1	Fluorescence	141
A.2.2	Auger Transitions	142
A.2.3	Coster-Kronig Transitions	144
A.2.4	Shakeoff Electrons	145
B	Modelling the Intrinsic Spatial Resolution of a Xenon Detector	146
C	A Simple GMD Simulation	148
D	Measuring the Spatial Charge Distribution in the GMD	151
	References	153

List of Abbreviations

ADC	analog-to-digital converter, analog-to-digital conversion
CCD	charge-coupled device
CR	computed radiography
CRPP	Centre for Research in Particle Physics
CSDA	continuous slowing-down approximation
CT	computed tomography
DF	digital fluoroscopy
DPA	dual photon absorptiometry
DQE	detective quantum efficiency
FOV	field of view
FWHM	full-width half maximum
GMD	gas microstrip detector
LSF	line-spread function
MCA	multi-channel analyzer
MGC	micro-gap counter
MTF	modulation transfer function
MWPC	multiwire proportional counter
NTP	normal temperature and pressure, 293 K and 1 atm (101.3 kPa)
PC	personal computer (microcomputer)
RMS	root mean square
SDRD	Siberian Digital Radiographic Device
SNR	signal-to-noise ratio
SPA	single photon absorptiometry

SPR	scanned projection radiography
SSD	silicon strip detector
TDI	time domain integration

List of Tables

2.1	Probability of emission per interaction, mean free path, and half-value layer of K and L fluorescence photons in xenon.	28
2.2	Probability of emission per interaction, mean ionization range, and multiple scatter range for K and L Auger electrons in xenon.	28
2.3	Electronic noise to centroid error conversion factor.	40
6.1	Spatial frequency [lp mm^{-1}] at which $\text{MTF}(f)$ crosses 0.05.	90
6.2	Gain curve fit parameters.	104
6.3	Fluence rate [$\text{mm}^{-2}\text{s}^{-1}$] at which the gain falls by 10%.	105
6.4	Predicted Space-Charge Limited Exposure Rates [mR s^{-1}] at 18 keV.	110
6.5	Energy Resolution (FWHM) of the GMD for Argon and Xenon at 1 atm.	114
6.6	Rejection of events and image generation efficiency.	124
A.1	Xenon electron binding energies (absorption edges) in keV.	143
A.2	Vacancy probabilities for xenon.	143
A.3	K-fluorescence lines and relative intensities for xenon.	143
A.4	L fluorescence in xenon according to mode of vacancy production.	143
A.5	K Auger electron average energies and relative probabilities.	143
A.6	L Auger emission in xenon according to mode of vacancy production.	143
A.7	Xenon L shell Coster-Kronig transition probabilities	143
A.8	Average L-fluorescence energies for xenon by subshell.	144

List of Figures

1.1	An example of the metal strip pattern in a GMD.	11
1.2	Concept diagram of the GMD as used in our imaging system.	14
2.1	Schematic diagram of our gas microstrip detector.	16
2.2	Quantum efficiency of xenon for different x-ray spectra.	19
2.3	Interaction coefficients of xenon at 20°C.	23
2.4	The relaxation cascade following photoelectric absorption, giving the probability ratios for each branch point.	25
2.5	Mean ionization range of K, L, and M photoelectrons in xenon.	28
2.6	Theoretical spatial resolution of a xenon x-ray detector.	31
2.7	(a) Electron drift velocity and (b) electron diffusion after 1 cm of drift as a function of reduced field E/P for different Xe:CH ₄ mixtures at 20°C.	33
2.8	Drift velocity of Xe ⁺ ions in Xe as a function of E/P at 20°C.	35
2.9	Simulated profile through a GMD image, demonstrating the effect of varying the diffusion.	38
2.10	Simulation of the effect of unequal anode gains.	42
3.1	The GMD imaging system.	44
3.2	Full scale drawing of the GMD and pressure window.	47
3.3	The electrical connections to the GMD.	50
3.4	Simplified diagram of the output electronics, including the ADC electronics (top), MCA electronics (middle) and discriminator electronics (bottom).	53
3.5	The trigger circuit (top) and the realtime/livetime circuit (bottom).	55
3.6	(a) ADC imaging electronics, and (b) discriminator imaging electronics.	56
3.7	The MCA built into the readout electronics.	56
3.8	Floor plan of the x-ray facility.	59
4.1	The programs and data files involved in the image generation process.	62
4.2	A typical single-anode spectrum, showing the quantities used in the calibration.	66

4.3	Relative gains α_i of the sixteen channels in the electronics.	68
4.4	Uncorrected profile image of a blank radiation field.	69
4.5	The calculated centroid $\hat{x}$ vs. the actual event location x using 3 channels, 4 channels, and the average of 3 and 5 channels assuming a $\sigma = 200 \mu\text{m}$ Gaussian charge cloud.	72
4.6	Simulations of various centroid methods.	73
5.1	The bar and star test patterns.	81
6.1	MTF for different x-ray spectra with 3.9 mm of xenon at 1 atm. . . .	92
6.2	MTF at different pressures for low kV_p beams.	92
6.3	MTF at different xenon pressures for 30 $\text{kV}_p + 1.2 \text{ mm Al}$ filtration. . . .	93
6.4	MTF at different xenon pressures for 50 $\text{kV}_p + 2.4 \text{ mm Al}$ filtration. . . .	93
6.5	Improvement of MTF with increased filtration.	94
6.6	Bar pattern images.	96
6.7	Star pattern images for different x-ray energies.	97
6.8	Comparison of the measured σ_x with the theoretical σ_{gas}	99
6.9	Line-spread function (solid line) and collected charge distribution (dashed line) at 13 kV_p for xenon at 3 atm.	101
6.10	Gas gain vs. V_c for a GMD with 7 μm anodes.	103
6.11	Gas gain vs. V_d for GMD with 7 μm anodes and a 3.9 mm drift gap with V_c set at -442 V.	103
6.12	Relative gain vs. rate, measured from detector current.	107
6.13	Relative gain vs. rate, measured from MCA peak position.	107
6.14	Relative gain vs. rate at 4 atm.	109
6.15	Iron-55 spectrum obtained with argon at 1 atm.	112
6.16	Americium spectrum obtained with xenon at 1 atm.	112
6.17	Unfiltered 30 kV_p tungsten spectrum at 1 atm.	113
6.18	Spectra used for spatial resolution measurements with 1 atm xenon. . . .	115
6.19	10 and 13 kV_p spectra obtained with xenon at 1–4 atm.	116
6.20	30 kV_p spectra obtained with xenon at 2–4 atm.	117
6.21	50 kV_p spectra obtained with xenon at 2–4 atm.	117
6.22	Several images obtained with Xe:CH_4 in the GMD, magnified 10 $\times$	120
6.23	Image of a ball grid array, with profiles taken through the solder balls. . . .	122
6.24	Image of a very fine copper braid obtained at 13 kV_p	123
6.25	Images of a small snail shell.	126
6.26	Resolution enhancement/degradation by energy selection.	127
7.1	Concept diagram of a keystone geometry detector for use in scanned-projection radiography or benchtop CT.	136
7.2	Sketch of a keystone print pattern.	136
C.1	Simulated events in the GMD.	150

D.1	Line-spread function (solid line) compared to collected charge distribution (dashed line) and the spatial charge distribution (dash-dotted line).	152
-----	---	-----

Chapter 1

Introduction

This chapter provides an introduction to the field of digital radiography and many of the x-ray detectors, both in use and under development, which can be applied to digital radiography. The use of the gas microstrip detector (GMD) as a digital imaging device will be discussed in Section 1.4.2. A summary of the previous research at Carleton University in imaging with the GMD is provided at the end of the chapter.

1.1 Digital Radiography

Digital radiography is defined as the acquisition, storage, manipulation, and display of x-ray images in digital format. The use of digital radiography in hospitals can be traced to the development of commercial computed tomography (CT) scanners *circa* 1973, when x-ray images were first generated in a computer rather than on film. Over the following years, there was a gradual development of digital techniques which could replace film for standard projection radiography. Over the last decade, the development of these techniques has accelerated and some are used clinically.

The categories of digital projection radiography for which commercial devices are being produced include 1) digital fluoroscopy, in which the image produced by an x-ray image intensifier is captured with television camera and video digitizer, 2) computed radiography, in which a photostimulable phosphor plate is exposed to x rays and the latent image is digitally scanned from the plate, 3) photoreceptor systems, in

which a fluorescent screen is coupled to a photo-sensitive digital device, and 4) direct conversion systems, in which the x rays ionize the detector and the resulting charge pattern is read out directly.

One primary purpose of this work is to bring attention to a fourth category, photon-counting radiography, in which the signal produced by each x ray is read out individually. Such systems are under development in many laboratories around the world [1] [2] [3] [4], and one has been used clinically [5].

1.1.1 Conventional Radiography

The image receptor in most common use today is the screen/film system, which generally consists of a piece of double-emulsion film sandwiched between two fluorescent screens in a cassette. When the screen/film cassette is exposed to x rays, the screens emit fluorescence light each time they absorb an x ray. The fluorescence light, in turn, exposes the film. The technology behind screen/film systems is highly advanced, and is still undergoing development [6] [7] [8].

The primary difficulty with screen/film radiography is that the image cannot be adjusted after it has been developed. Quality control in the imaging facility ensures that the best exposure is used for the diagnostic problem under consideration, but film has a limited latitude and details are lost in areas of the image where the exposure is much higher or much lower than the average.

1.1.2 Motivations for Digital Radiography

1.1.2.1 Flexibility/Portability

One of the advantages of digital radiography is that the contrast levels are adjustable, so the exposure is relevant only in that the number of photons recorded must be adequate for the details in the image to be seen. This allows one to be less specific in the applied technique and still obtain a usable image, by adjusting the contrast after exposure. This is of particular advantage, for example, in mobile x-ray units which must serve a variety of purposes under less than ideal conditions.

More importantly, the contrast levels can be adjusted while the radiologist is making a diagnosis. If a particular object in the image looks suspicious, the contrast of that object can be enhanced while the image is being viewed.

Digital images also have the advantage that they can be stored, sorted, retrieved, and, very importantly, duplicated with greater ease than film images, and all with absolutely no degradation. Also, with the image in digital form, analysis algorithms can be applied to aid or even to automate the diagnostic assessment of the images [9].

1.1.2.2 Image Quality

Even with the many advantages of digital radiography already given, the medical community is unwilling to accept any digital technique unless the images have been shown to be of equal or greater diagnostic value than screen/film images.

The image quality obtained for a specific radiation exposure to the patient depends on the contrast, the spatial resolution, and the detective quantum efficiency (DQE).

Contrast is adjustable in digital images, and therefore not an issue as long as the dynamic range is sufficient. Resolution and DQE, then, are the criteria by which digital techniques are usually judged.

Most digital systems do not have the resolution of screen/film systems, usually because the pixels are not small enough. However, this is not a problem as long as the resolution is suitable for the diagnostic task under consideration. Zhao and Rowlands [10] quote $200\text{ }\mu\text{m}$ as a suitable pixel size for chest radiography, and Säbel and Aichinger [11] place the maximum pixel size for mammography at $50\text{ }\mu\text{m}$.

The detective quantum efficiency is the efficiency with which the information (measured as the square of the signal-to-noise ratio) in the incident x rays is transferred to the image. Some digital techniques, in particular direct x-ray conversion techniques, have the potential to surpass the DQE of film/screen systems. Most other digital techniques rely, like screen/film, on the conversion of the x rays into light by a fluorescent screen which must be coupled to a photoreceptor. The primary cause of efficiency loss in these systems is that the thickness of the screen must be limited in order to reduce the blurring of the image.

1.2 Comparison of Digital Radiography Methods

1.2.1 Digital Fluoroscopy

Digital fluoroscopy (DF) involves the use of a video digitizer to capture an image from a television camera coupled to an x-ray image intensifier tube. The most widely used digital imaging method in hospitals today. DF is used primarily for vascular imaging via a technique known as digital subtraction angiography (DSA). In DSA, a digital image is obtained of the patient's anatomy in an area of interest, and is subtracted from subsequent images of the same area in which a contrast agent has been injected into the bloodstream. The resulting images show the vasculature clearly where contrast agent is present and the remainder of the image is blank, providing superb vascular contrast. A description of DSA is provided in many standard references, including Wolbarst pp. 312-317 [12] and Webb pp. 70-71 [13].

1.2.2 Computed Radiography

Computed radiography (CR) is the only mode of digital radiography for large-area images which has established itself within hospital radiology departments. The basis of CR is the photostimulable phosphor plate, which stores a latent image after being exposed to radiation. After being exposed, the plate is scanned with a laser beam which releases the latent image in the form of stimulated luminescence. An examination of previous and current CR systems is provided by Dobbins *et al* [14]. CR imaging systems are manufactured by Eastman Kodak, Fuji, and AGFA.

1.2.3 Screen/Photoreceptor Systems

Because the screens developed for screen/film radiography have had the benefit of decades of refinement, there has been a large amount of research put into coupling screens to photosensitive digital detectors. The most commonly used detectors are charge-coupled devices and photodiodes.

1.2.3.1 Charge-Coupled Devices

The charged-coupled device (CCD) is a small, very high resolution photo-sensor which forms the basis for modern digital photography. One difficulty in using a CCD as an image receptor for radiography is that the sensitive area of a CCD is on the order of one hundredth the area of the image projected onto the fluorescent screen, so a lens system is required to demagnify the image by a factor of ten or so. Designing such a system is a formidable task because the amount of light lost in the lens system must be kept to a bare minimum. Lens coupling efficiency for radiography is discussed by Yu and Boone [15].

Another option for demagnification is to use an array of tapered optical fibres (referred to as a fibre optic taper), which provides efficient coupling between the screen and the CCD. A demagnification factor of only four is currently available, so more than one CCD must be used for the entire image to be received at once. Hejazi and Trauernicht [16] provide a theoretical treatment of both fiber optic and lens demagnification.

1.2.3.2 Photodiode Arrays

A better option than using a CCD is to use a large array of photodiodes. When this is done, a layer of scintillator can be deposited directly on top of the photosensitive surface of the diodes, eliminating the need for an optical coupling system. The readout of the photodiodes is accomplished by an active matrix, a technology developed for flat-screen computer monitors which consists of a thin sheet of electronic components. Such a system has been developed by Antonuk *et al* [17].

1.2.4 Direct Conversion Systems

Direct conversion systems fall into two very different categories, solid state and gas state. The basic principle is the same for both: the charge produced when the detector is ionized by radiation is measured and used to form the image.

1.2.4.1 Selenium-based Systems

Selenium is a photoconductor, meaning that it is normally an insulator but becomes a conductor in the presence of light. This property of selenium is the basis of modern photocopying and laser printing, and the fact that it also becomes a conductor in the presence of x rays has led to its use in digital radiography. In a photocopy machine, the surface of a selenium drum is charged and then exposed (line-by-line as the drum turns) to the image of a page. The charge leaks away where the drum is exposed, and when the drum is subsequently dusted with toner the toner sticks only to the unexposed areas. The toner is then transferred to and fused to a sheet of paper.

In 1973 a radiographic technique called xeroradiography was developed based on the same principle [18], but using x rays instead of light and a flat selenium plate instead of a drum. It has been many years since xeroradiography was in clinical use, primarily because it was less sensitive than screen/film (Dance [19]). The Thoravision digital chest imaging system currently sold by Philips Medical Systems operates on the same principle, but uses a selenium drum and reads out the charge with an array of electrostatic probes. The Thoravision system has recently undergone clinical evaluation [20] [21] with positive results.

Another readout method for use with a thin selenium sheet is to apply a bias voltage between the two faces of the sheet, and expose one face to radiation. Charge is transferred between the electrodes proportional to the exposure and collected on an array of capacitors, which are coupled to an active matrix which reads out the charge. Rowlands *et al* [22] [10] and Lee *et al* [23] have developed such devices, the latter being marketed by Sterling Diagnostic Imaging.

1.2.4.2 Gas-Filled Detectors

The simplest form of gas-filled detector is the ion chamber, in which a high potential across the gas is used to collect (in the form of charge) the ionization produced by radiation. In order for gas-filled detectors to have high x-ray interaction efficiency, dense gases such as xenon must be used.

Ionography systems, developed soon after xeroradiography, use a large, flat ion chamber and collect the ionization charge on a mylar foil. The foil is either developed with toner, or scanned by an electrostatic probe [24] to produce a digital image. Ionography has been commercially unsuccessful, likely due to its complexity compared to screen-film (Johns and Cunningham pp. 629–630 [25]).

Linear-array ion chambers, for which the ionization charge is read directly into the electronics via an array of electrodes, have been used in CT scanners [26] and in a prototype projection radiography system [27] [28].

A particularly interesting class of gas-filled detector is the avalanche counter, which is designed and operated such that gas multiplication occurs (a process which will be described in Chapter 2). As a result of gas multiplication, the ionization charge produced by each individual x ray will result in a charge signal from the detector which is large enough to be measured. Such detectors are said to be capable of photon counting. The detectors which fall into this category are multiwire proportional counters, gas microstrip detectors, and their derivatives. These detectors will be described in detail in Section 1.4.

1.3 Scanned Projection Radiography

Digital imaging detectors may be placed into two categories: those which have a large enough field of view (FOV) to capture an entire image at once, and those which do not. Detectors with an FOV equal to the desired image size are generally favored by manufacturers and imaging technicians because they are more easily integrated with existing film/screen equipment. However, these detectors are usually quite expensive because of the difficulty of producing such a large device, $18 \times 24 \text{ cm}^2$ with $50 \mu\text{m}$ pixels for mammography [11] or $35 \times 43 \text{ cm}^2$ with $200 \mu\text{m}$ pixels for general radiography [10].

Scanned projection radiography (SPR) methods allow the use of a detector with an FOV as large as the image in only one of the two dimensions. The x rays are collimated into a fan beam before and after the object to irradiate only the FOV of the detector. The two collimators and the detector are scanned synchronously over the full image area.

One attraction of SPR is that the radiation scattered out of the fan beam by the patient will not be detected. In full-area radiography, the scattered radiation incident on the detector is a major source of image degradation [29].

SPR techniques suffer, however, from less efficient use of the x-ray tube output than full-field techniques. An x-ray tube can only provide a limited exposure before overheating; hence, if a very thin fan beam is used, multiple x-ray exposures (with a cooling period between exposures) might be required. This problem can be alleviated by the use of high-output x-ray tubes (the solution to the same problem in CT scanners) or by using multiple fan beams and detectors.

1.3.1 Slot Scanning

Most proposed SPR systems use a fan beam a few mm or cm wide and apply the technique of time domain integration (TDI) to keep the image from being smeared by the scanning motion of the detector. The basic idea behind TDI is that the signal used to form the image (usually charge) is integrated at pixel locations which are stationary with respect to the object, rather than being stationary with respect to the scanning detector. This is accomplished by the transformation $x = x'; y = y' - v(t - t'_0)$ where (x, y) are the coordinates in the stationary frame of reference, (x', y') are the coordinates in the detector frame of reference, v is the scan velocity, and $t - t_0$ is the time elapsed since the start of the scan.

In the CCD slot-scan system proposed by Maidment and Yaffe [30], the charge in the CCD pixels is clocked to shift across the CCD at a velocity equal and opposite to the scan velocity.

For linear-array ion chambers a TDI technique known as kinestatic imaging has been developed by DiBianca and Barker [31], who match the ion drift velocity in the chamber to the scan speed. The charge is integrated in the gas as it drifts, and is read out by strip electrodes along the trailing edge of the detector.

A photon-counting detector with two-dimensional readout could also be used in a slot scanning system, because the time of arrival t of each photon is known and the transformation $y = y' - v(t - t'_0)$ can be applied to the position of each photon.

1.3.2 Slit Scanning

The SPR method we apply in our imaging system is slit scanning, which uses a very thin fan-beam of x rays to eliminate image blurring rather than using TDI. The detector provides a single image coordinate x , the other coordinate being provided by the scan location y .

Slit scanning provides essentially complete x-ray scatter rejection, but the x-ray tube output is used extremely inefficiently. SPR systems based on the use of slit scanning have also been built by many other groups [2] [27] [32].

1.4 Imaging with Gas Avalanche Counters

All gas avalanche counters proposed for digital radiography fall into the category of proportional counters. Proportional counters are capable not only of photon counting but also of measuring the energy deposited by each photon.

1.4.1 Multiwire Proportional Counter

The multiwire proportional counter (MWPC) was the first gas avalanche counter used for imaging. It consists of fine (10–25 μm) anode wires strung parallel to each other in a plane through a gas volume, with one plane of cathode wires strung above the anode plane and another below. The gas and the three wire planes are contained within a flat, sealed box. The avalanche occurs in the high electric fields surrounding each anode wire.

The feasibility of a xenon-filled MWPC as an imaging device was first investigated by Bateman *et al* in 1976 [33]. Actual devices were built and medical images obtained by Baru *et al* in 1984 [34] and by Angelini *et al* in 1989 [35].

1.4.1.1 Siberian Digital Radiographic Device

The device made by Baru *et al* [34], referred to as the Siberian Digital Radiographic Device (SDRD), obtains images by scanned projection radiography. The

anode wires are strung in a keystone geometry, meaning that each wire points towards the x-ray source. This allows the detector to be made very deep, because each photon path is parallel to a wire and there is no parallax error. Their current device [32] has a wire spacing of 1.2 mm and uses coincidence and anti-coincidence between adjacent wires to produce a pixel size of 0.6 mm.

The SDRD has been in clinical use in Russia for several years. An evaluation of the device as compared to modern screen/film radiography revealed that patients examined with the SDRD received less than 1/5 the dose for chest examinations as those examined in a hospital in Britain, and only 1/280 the dose for abdominal examinations [5]. However, the SDRD provides lower resolution than screen/film so it is expected that fewer photons would be required to produce an image with good contrast/noise ratio.

1.4.1.2 MWPC Bone Densitometer

Angelini *et al* [35] have developed a small full-area MWPC imaging system for bone densitometry. The x rays enter perpendicular to the plane of the device as they do in flat panel imaging systems, in contrast to the keystone geometry used in the SDRD. The cathodes in the planes above and below the anode plane are strung perpendicular to each other, permitting the x and y coordinates of each x ray interaction to be measured. The device provides a 128 mm $\times$ 128 mm image area with 1 mm pixels.

The detector is used for both single and dual photon absorptiometry (SPA and DPA), for which a bone is imaged *in vivo* using either one or two external radioactive sources in order to determine the bone mineral content.

Two limitations of the MWPC system as compared to screen/film SPA and DPA systems were its resolution and its bulkiness. The device was found, however, to require a lower dose to the patient per examination.

Figure 1.1: An example of the metal strip pattern in a GMD. The narrow strips are the anodes, around which the gas avalanche occurs, and the wide strips are the cathodes, at which the ions are collected.

1.4.2 The Gas Microstrip Detector

The GMD, developed in 1988 by Oed [36], is very similar in concept to the MWPC except that the anodes and cathodes are strips printed onto a flat plate rather than being wires strung through the gas (see Figure 1.1). The plate provides mechanical support for the wires, allowing them to be finer and closer together: the typical anode pitch for a GMD is $200\text{ }\mu\text{m}$, compared to 1 mm for an MWPC.

1.4.2.1 Imaging with the GMD

The first x-ray image obtained with a GMD was published in 1992 by Angelini *et al* [37]. Their GMD used a two-dimensional readout scheme, which employed a set of backplane strips set orthogonal to the anode/cathode strips and separated from them by a $1.8\text{ }\mu\text{m}$ layer of SiO_2 . It provided a $13\text{ mm} \times 13\text{ mm}$ imaging area. More recently, Ochi and Tanimori [4] produced a $20\text{ mm} \times 20\text{ mm}$ image with a device similar to that of Angelini, but using polyimide instead of SiO_2 .

1.4.3 Micro-Gap Counter

The micro-gap counter (MGC) was developed in 1992 by Angelini *et al* [38]. It is similar in concept to the GMD, except that rather than the anodes and cathodes being placed side by side, the anodes are printed on top of the cathodes and are separated from them by a $15\text{ }\mu\text{m}$ thick insulator the same width as the anodes.

This extremely narrow gap allows for rapid charge collection, and in addition, the cathodes are usually printed orthogonal to the anodes to provide two-dimensional readout. However, the fabrication is more complicated than for the GMD and the cost per device is considerably higher.

1.4.4 Microdot Chamber

The microdot chamber, developed by S.F. Biagi *et al* [39], is a natural extension of the GMD from a strip detector to a pixel detector. Each element consists of a 20 μm diameter anode dot encircled by a 200 μm diameter cathode ring. Though the microdot chamber could conceivably be used with true pixel readout, the anode dots are read out in lines by an array of readout busses buried beneath the dots. The cathodes are connected together in lines orthogonal to the anode lines to provide two-dimensional position readout.

1.5 Silicon Strip Detectors

The silicon strip detector (SSD) predates the GMD by eight years, being developed in 1980 by Kemmer and substantially improved in the following years [40]. Like the GMD, the SSD has high spatial and energy resolution and is capable of photon counting at high rates. The development of SSD-based imaging systems has been parallel to that of GMD-based imaging systems.

An SSD consists of a large wafer of silicon with n^+ doping on one face and thin strips of p^+ doping on the opposing face. A bias voltage applied between the n^+ face and each of the p^+ strips creates a depletion region in the silicon beneath each strip, and any holes (positive charges) produced in the depletion region by radiation are collected on the strips. The strip pitches used vary from 25 μm [41] to 200 μm [2].

The SSD does not have an intrinsic gain mechanism as the GMD does. It takes only 1.1 eV to produce an elementary charge in silicon, however, as compared to 22 eV in xenon, so an SSD provides essentially the same charge signal as a GMD operated with a gain of 20.

Arfelli *et al* [2] [42] [43] have developed a photon-counting SPR system based on a 200 μm -pitch SSD, with which they have obtained several images of a mammographic test phantom.

1.6 Gas Microstrip Detector Imaging at Carleton University

Gas microstrip detector imaging research at Carleton University is a shared project between the Centre for Research in Particle Physics (CRPP) and the Department of Physics. The project follows earlier research in developing gas microstrip detectors for use in high-energy physics experiments [44] [45] [46]. The GMD imaging research group was formed in 1994 and its membership includes Madhu S. Dixit, Jacques Dubeau, and F. Gerald Oakham at the CRPP, and John C. Armitage, Paul C. Johns, and Dean Karlen in the Department of Physics.

The initial work on the present imaging electronics was begun in 1995 [47] by Madhu Dixit and Ernie Neuheimer, the CRPP electronics designer. The original data acquisition software and image generation software were written by Dean Karlen. The result was a scanned projection radiography system capable of producing small (2.6 mm wide) images, based on the detector orientation shown in Figure 1.2.

During the summer of 1995 two summer students, Luca Diaconescu and Magdalena Grabari, continued to improve the electronics, data acquisition software, and image generation software [48]. They were followed by Derek Bouius in the fall who increased the gas pressure to 2 atm and measured a corresponding increase in spatial resolution. Derek was assisted by Ken Leong, a high school student hired to work in the laboratory. At the time I began my research, the GMD was housed inside a sealed pressure vessel filled to 2 atm with a 9:1 argon:isobutane gas mix and was operating reliably. Some of my work has been presented at various conferences by myself [49] [50] and others [51] [52].

Figure 1.2: Concept diagram of the GMD as used in our imaging system.

1.7 Thesis Overview

The purpose of the work described in this thesis was to determine whether a GMD filled with xenon above atmospheric pressure would be suitable for digital radiography. The purpose of the current chapter was to provide a background of the work already done by our group and other groups relating to photon-counting digital radiography, within the broader context of digital radiography.

The following chapter (2) describes the theory of GMD operation relating to its use and to its performance as an imaging detector. Subsequent chapters describe, in order, (3) our GMD and our scanned-projection radiography system, (4) the software we use to generate images from the data provided by the GMD, (5) the methods used to measure system parameters relevant to digital radiography (in particular spatial resolution and counting rate), and (6) the results of the measurements and example images.

The final chapter (7) provides a discussion of the results in the context of both how well they agree with theory and what they mean regarding the use of the GMD for digital radiography. The end of the chapter provides suggestions for future work with the GMD scanned projection radiography system.

Chapter 2

Theory

This chapter is divided into four sections. The first section gives an overview of gas microstrip detector operation and provides a framework for the rest of the chapter. The other sections cover, in order, the interaction of x rays with xenon, the charge collection and readout, and the determination of the coordinate of the x-ray interaction from the measured charge distribution.

2.1 Principles of GMD Operation

The gas microstrip detector was introduced in the previous chapter. Its main features are an entrance window through which x rays enter the detector to interact with and ionize the gas, a drift region over which charge is collected, and a charge multiplication region in which very high electric fields produce gas gain (see Figure 2.1).

2.1.1 Signal Development

The GMD is operated in the proportional regime, where the charge collected in the detector following each photon interaction is given by

$$Q = eME_{ab}/W \quad (2.1)$$

where e is the elementary charge, M is the gas gain, E_{ab} is the energy absorbed by the detector, and $W = 22$ eV/ion pair is the average energy required to liberate an

Figure 2.1: Schematic diagram of our gas microstrip detector, showing the electric field lines which the electrons follow towards the anodes.

electron from a xenon atom. The value of W varies slightly with energy — Santos *et al* [53] have done detailed Monte-Carlo simulations which predict values of 22.5 eV at 6 keV and 21.7 eV at 30 keV. Their simulation also shows a jump of ~ 0.5 eV in the value of W at the xenon M and L edges (1 and 5 keV), and it can be assumed that there is also a discontinuity at the 35 keV K edge.

In our use of the GMD for digital radiography the number of primary electrons produced per x ray is ~ 500 and the gas gain is ~ 500 , providing a signal on the order of 2.5×10^5 electrons or 40 fC.

The usual sequence of events following the interaction of a photon in the GMD is as follows. First, the absorption of an x-ray photon by a single gas atom results in the ejection of a photoelectron, followed by a shower of electrons and fluorescence photons as the atom relaxes to its ground state. The photoelectron and the other electrons are absorbed by the surrounding gas, while the fluorescence photons are either absorbed or escape from the detector. The result is a cloud of ionization around

the interaction site containing E_{ab}/W electron-ion pairs. E_{ab} being the photon energy less the energy of the escaped fluorescence. The electrons in this cloud are called the primary electrons.

The primary electrons travel up the electric field lines to the multiplication region, where the electric potential around the anodes changes rapidly enough along the electron's drift path that the energy gained between inelastic collisions is greater than the ionization potential of the gas. Each electron produces an additional electron-ion pair for, on average, each ionizing collision. The result is an avalanche of electrons "falling" up the electric potential towards the anode. The production of the electron avalanche is described in several standard references, including CERN-77 [54].

Because most avalanche electrons are produced within a few μm of the anode, they travel through a fairly small potential before being collected and do not form a significant portion of the total induced charge signal. The ions, however, move swiftly away from the anode through a very rapidly changing potential and induce an easily measured signal in the detector. As the ions move further from the anode they slow down and the electric fields become smaller, resulting in a gradual rise of the induced charge signal after the initial fast rise.

2.1.2 Detector Efficiency

The detective quantum efficiency (DQE) of a detector is a measure of how well the system captures the signal-to-noise ratio (SNR) of the primary radiation beam incident upon it. The definition of DQE is (Barrett and Swindell p. 194 [55])

$$\text{DQE} = \frac{\text{SNR}_{\text{out}}^2}{\text{SNR}_{\text{in}}^2} \quad (2.2)$$

The DQE of the GMD imaging system can be expressed as the product of two factors:

$$\text{DQE} = \eta_{\text{QE}} \eta_{\text{gen}}. \quad (2.3)$$

The first factor η_{QE} is the quantum efficiency, which is the ratio of the number of x rays which interact with the detector to the total number of x rays incident on the detector. The second factor η_{gen} is the image generation efficiency, which is the probability that a photon which interacts will contribute to the image.

2.1.2.1 Quantum Efficiency

For monochromatic x rays of energy E , the probability that a photon will be transmitted through the window and then interact in the detector is given by

$$\eta_{QE} = e^{-\mu_w(E)t_w} (1 - e^{-\mu(E)t}) \quad (2.4)$$

where $\mu_w(E)$ and $\mu(E)$ are respectively the total attenuation coefficient for the window material and for xenon. t_w is the thickness of the window, and t is the depth of the drift region in the GMD. In order to calculate η_{QE} for a polychromatic x-ray beam, the above expression must be integrated over the spectrum.

Figure 2.2 gives the quantum efficiency vs. the thickness-pressure product of the detector for x-ray spectra similar to those used in medical radiography. The spectra in the figure were taken from Birch and Marshall [56], with filtration being simulated using the interaction data in UCRL-50400 [57]. The filtration through water is meant to simulate the hardening of the beam transmitted through the patient. The attenuation due to the window has been neglected in the figure because it will vary from one detector to the next. In our system (Figure 2.1), the window absorbs approximately 10% of the x-rays at 30 kV_p and less for higher energies.

2.1.2.2 Image Generation Efficiency

There are several ways in which the DQE can be reduced during the generation of the image from the signals from the GMD. In the data acquisition trigger which signals the recording of an x-ray event, x rays may either fail to produce a trigger or may be obscured by triggers resulting from electronic noise. Also, at the time of the generation of the image from the data, the system may choose to reject certain events either because they have the characteristics of noise events or because the system cannot accurately reconstruct the position of the x-ray.

The following quantities can be used to describe the image generation efficiency: N_0 is the number of photons which interact in the detector, N is the number which trigger an event acquisition, and N_r is the portion which produce a trigger but are subsequently rejected from the image. In addition, N_n is the number of noise events

Figure 2.2: Quantum efficiency of xenon for different x-ray spectra.

and N_{nr} is the number of those which are rejected.

The square of the SNR of the image is

$$\begin{aligned} \text{SNR}_{\text{image}}^2 &= \frac{(N - N_r)^2}{\sigma_{(N - N_r + N_n - N_{nr})}^2} \\ &= \frac{(N - N_r)^2}{N - N_r + N_n - N_{nr}} \end{aligned}$$

Dividing this by the SNR^2 of the photons interacting in the detector, which is simply equal to N_0 , provides

$$\eta_{\text{gen}} = \frac{N}{N_0} \left(1 - \frac{N_r}{N} \right) \left[1 + \frac{N_n - N_{nr}}{N - N_r} \right]^{-1}. \quad (2.5)$$

The three factors represent, in order, 1) the fraction of interactions which produce a trigger, 2) the fraction of interactions which are not rejected during image generation, and 3) the degradation of the image by noise events. The first factor will be very close to unity because the high gain of the GMD provides an excellent trigger efficiency, and the third factor can generally be neglected because noise events are both rare and easily recognized. The second factor is 0.80–0.95 for the rejection criteria we

currently apply during image generation, but one could relax the criteria and suffer a penalty in spatial resolution rather than in DQE.

2.1.2.3 Swank Factor

One important factor in the DQE which is present in energy-integrating detectors, which include virtually all detectors currently used for radiography, but is not present in photon-counting detectors is the Swank factor (Barrett and Swindell p. 285 [55])

$$\eta_{\text{swank}} = \frac{\bar{E}_s^2}{\overline{E_s^2}}. \quad (2.6)$$

The mean values $\bar{E}_s$ and $\overline{E_s^2}$ are calculated over detector's signal spectrum, i.e. the spectrum of signal values resulting from a particular incident x-ray field. Typically $\eta_{\text{swank}} \approx 0.8\text{--}0.9$ [55], so a counting detector with perfect event rejection would be 10–25% more efficient than an equivalent integrating detector.

2.1.3 Spatial Resolution

The modulation transfer function $\text{MTF}(f)$ describes how well each spatial frequency f is transferred through the imaging system (see Barrett and Swindell p. 39 [55] or Johns and Cunningham p. 597 [25] for a mathematical description). The MTF is unity at $f = 0$ by definition, and falls (though not necessarily monotonically) to zero as $f \rightarrow \infty$. The MTF, like the DQE, can be expressed as the product of factors relating to the steps leading to the formation of an image:

$$\text{MTF}(f) = M_{\text{gas}}(f) M_{\text{gen}}(f) \quad (2.7)$$

where $M_{\text{gas}}(f)$ is determined by the symmetry of the primary charge cloud, and $M_{\text{gen}}(f)$ by the noise in the signals from each anode and the suitability of the method used to generate the positions of the x-ray interactions from the signals.

In general, $M_{\text{gas}}(f)$ is the limiting factor in the GMD resolution. It scales in f proportional to the pressure P (i.e. $M_{\text{gas}}(f; P) = M_{\text{gas}}(f P_0 / P; P_0)$ for an arbitrary reference pressure P_0), and depends on the x-ray energy as discussed in Section 2.2. At high pressure and very low energy, the primary ionization cloud is very small

and $M_{\text{gen}}(f)$ becomes the limiting factor. Ultimately, in the limit of extremely high pressure, a geometrically flawless GMD, and noise-free electronics, the MTF will be limited by the statistics of the electrons in the primary charge cloud.

Equation 2.7 is only strictly true if all of the factors are stationary, meaning that they do not depend on the position x where the x ray interacts. $M_{\text{gas}}(f)$ is stationary, but $M_{\text{gen}}(f)$ depends on where the photon interacts with respect to the nearest two anodes, i.e. on the spatial phase.

If the phase-averaged value of $M_{\text{gen}}(f)$ is used, then Equation 2.7 accurately gives the phase-averaged MTF. Phase averaging is accomplished by averaging the MTF over interaction positions $x = [x_0, x_0 + a]$ where x_0 is an arbitrarily chosen position and a is the anode pitch.

When calculating the theoretical spatial resolution, it is often easier to work in position or x space rather than in frequency or f space. The resolution is then expressed as the root mean square (RMS) error σ_x in determining the position of the x-ray interaction.

$$\sigma_x^2 = \sigma_{\text{gas}}^2 + \sigma_{\text{gen}}^2. \quad (2.8)$$

Note that it is not possible to convert from σ_x to $\text{MTF}(f)$ unless the shape of the error distribution function is known.

2.1.4 Energy Resolution

The definition of energy resolution used in this thesis is the ability to distinguish between different amounts of energy absorbed by the detector:

$$R = \frac{\Delta E_{\text{ab}}}{E_{\text{ab}}} \times 100\% \quad (2.9)$$

where E_{ab} is the energy absorbed in the detector as measured by the detector, and ΔE_{ab} is the full-width half maximum (FWHM) of the energy response curve. The reason that the definition is given in terms of absorbed energy, rather than incident energy, is because the response spectra of most detectors to a monoenergetic line contain more than one peak (due to fluorescence escape and incoherent scatter interactions).

The absolute limit to the energy resolution of any gas detector is the Fano factor, defined by the equation

$$F = \frac{\sigma_n^2}{\bar{n}} \quad (2.10)$$

where $\bar{n}$ is the number of primary electrons produced per interaction and σ_n^2 is the variance of that number. For xenon, F is equal to 0.24 at 10 keV (Dias *et al* [58]) and shows mild variation ($\pm 20\%$) with photon energy. Using $E_{ab} = W\bar{n}$, the intrinsic energy resolution of a gas-filled detector is

$$\begin{aligned} R_i &= \sqrt{\ln 256} \left(\frac{F}{\bar{n}} \right)^{1/2} \times 100\% \\ &= 2.355 \left(\frac{FW}{E_{ab}} \right)^{1/2} \times 100\% \end{aligned} \quad (2.11)$$

where $\sqrt{\ln 256} = 2.355$ is the ratio of the full-width half-maximum to σ for the Gaussian $\exp(-\frac{1}{2}(x/\sigma)^2)$.

The energy resolution is worse than this intrinsic value because different electrons follow different drift paths towards the anodes, and because the width and thickness of the anodes are not perfectly uniform. There is also some loss of energy resolution in the amplifiers and other electronics.

2.2 X-Ray Absorption in Xenon

This section addresses two items relating to the production of the primary charge cloud in xenon: the size and asymmetry of the charge cloud, and the loss of energy from the detector due to the escape of fluorescence photons or energetic electrons.

2.2.1 X-Ray Interactions

Because xenon has a high atomic number ($Z = 54$) and the x-ray energies used in medical radiography are below 150 keV, x-ray interactions occur primarily via the photoelectric effect (see Figure 2.3) with only minor contributions from coherent and incoherent scatter interactions.

Figure 2.3: Interaction coefficients of xenon at 20°C for (a) the entire diagnostic energy range and (b) low energies, allowing the three L-edges to be seen. The interaction coefficients were taken from UCRL-50400 [57].

2.2.1.1 Photoelectric Effect

When an x-ray photon of energy E interacts with an atom via the photoelectric effect, the atom absorbs the photon and ejects an electron of energy

$$E_e = E - E_X \quad (2.12)$$

where E_X is the binding energy of the atomic shell X which the electron was ejected from. A photoelectric interaction with a particular shell or subshell occurs only if $E \geq E_X$ and the probability of interaction increases as $E \rightarrow E_X$, giving rise to absorption edges for each shell which can be seen, for the K and L shells, in Figure 2.3. As shown in the figure, $E_K = 34.58$ keV and $E_L = 5.22$ keV. The L edges are close enough together that they can be treated as a single edge.

The relative probability that a photoelectric interaction will occur in a particular shell is called the vacancy probability V_X , which is given for xenon in UCRL-50400 [57]. For $E > E_K$, $V_K = 0.835$ and $V_L = 0.130$ (the balance, 0.035, occur in the M and higher shells). For $E < E_K$, $V_K = 0$ (interactions cannot occur in the K shell) and $V_L = 0.787$.

2.2.1.2 Coherent and Incoherent Scatter

Scatter interactions are those which involve the rebounding of photons from electrons. Because the photons are deflected from their original path, scatter within a detector results in a decrease in the spatial resolution (with the exception of “thin” detectors where the photon does not re-interact after being scattered; however, thin detectors are unsuitable for radiography due to their low quantum efficiency). In xenon, coherent scatter is the primary competitor to the photoelectric effect until 100 keV, at which energy incoherent scatter becomes more probable than coherent scatter.

In coherent scatter (cross section denoted by σ_{coh}) there is no energy transferred from the photon to the atom. However, the photon is deflected and any subsequent interactions will not be along the photon’s original path.

Incoherent scatter (denoted by σ_{incoh}) occurs when a photon rebounds from an electron in a billiard-ball type collision, the electron being ejected from the atom with energy

$$E_{\sigma} = E - E' - E_X \quad (2.13)$$

where E and E' are the initial and final photon energies and E_X is the binding energy of the shell which the electron was ejected from. Because the mean photon scattering angle is approximately 90° , incoherent scatter is particularly deleterious to the detector’s performance. For the 50 kV_p spectrum we use in our imaging system, incoherent scatter interactions make up less than 1% of the total and they can be ignored. For a 150 kV_p spectrum, by comparison, they would make up approximately 10% of the total.

2.2.2 Relaxation Cascade

After an electron has been ejected from an atom either by the photoelectric effect or by incoherent scatter, the atom produces several emissions as it relaxes to its ground state. These emissions consist primarily of fluorescence photons and Auger electrons. The process of relaxation is described in detail in Appendix A, and a summary is provided here.

Figure 2.4: The relaxation cascade following photoelectric absorption, giving the probability ratios for each branch point. In the top row the probabilities in parentheses are for $E_L < E < E_K$ where E is the energy of the incident photon, while the other probabilities are for $E > E_K$. The energy of each emission is given in the boxes.

A branch diagram of the relaxation process following the photoelectric effect is given in Figure 2.4. The second row of boxes indicates the three types of photoelectrons which can be produced, and gives their energy according to Equation 2.12. The boxes below indicate Auger electrons and fluorescence photons produced by the relaxation of the xenon atom. The diagram follows the relaxation process only to the L shell because the energies involved in the relaxation of M and higher shells are very small (typically less than 1 keV) and the emitted electrons and fluorescence photons have extremely short ranges.

Because xenon has a high atomic number, the K Auger electron energies are fairly high (24–33 keV). The range of these electrons in the detector is several mm atm and hence they, along with the photoelectrons, are what most seriously limit the resolution of the GMD.

2.2.3 Electron and Fluorescence Photon Ranges

This section provides equations relating the energies of photons and electrons to their ranges in xenon. This information is of critical importance to the spatial resolution of a xenon-based detector, and is also important to the energy resolution in that fluorescence photons and electrons can escape from the detector and distort the absorbed energy spectrum.

2.2.3.1 Photon Ranges

The best measure of the range of a photon is the mean free path λ , i.e. the average distance the photon travels before interacting. This is given by

$$\lambda(E) = \frac{1}{\mu(E)} \quad (2.14)$$

where $\mu(E)$ is the interaction coefficient. In determining what fraction of photons will escape from the detector a conceptually more useful quantity is the half-value layer $HVL = \lambda \ln 2$, which is the thickness of xenon through which a photon has a 50% probability of being transmitted.

Both λ and the HVL are given for K and L fluorescence photons in Table 2.1, along with the probability p of each fluorescence transition per photoelectric interaction. The ranges for L fluorescence have been separately averaged for incident photon energies both above the K edge and below the K edge, though the difference between the two averages is small.

Because the mean free path of M fluorescence photons is approximately $100 \mu\text{m atm}$ and the M shell fluorescence yield is less than 0.01, M fluorescence photons can be ignored.

2.2.3.2 Electron Ranges

There are three categories of electrons which can be set in motion by an x-ray interaction: photoelectrons, recoil electrons (from incoherent scatter interactions), and Auger electrons. Because incoherent scatter is relatively rare in xenon for diagnostic energy x rays, only photoelectron and Auger electron ranges will be provided in this section.

The electron range is generally defined to be the distance travelled by the electron before it stops. One measure of the electron range, the CSDA (continuous slowing down approximation) range, is the total path length of the electron track. It is found from the stopping power $S = dE/dx$ by integrating $1/S$ between the initial and rest energy of the electron.

The electron's path is far from straight due to multiple scattering off of other electrons, so the CSDA range is a poor measure of the final distance the electron travels from its point of production. A better estimate is the multiple-scatter range, for which a formula is given in Bateman *et al* [33].

$$R_e = 0.2115 Z^{0.26} E^{1.265-0.0954 \ln E}. \quad (2.15)$$

This equation (a variation on an empirical formula first proposed in 1951) uses units of MeV for energy and g cm^{-2} for distance. For xenon, $Z = 54$ is used and R_e must be divided by the density of xenon at NTP, $5.495 \times 10^{-3} \text{ g cm}^{-3}$ [59], in order for a range in cm atm to be obtained.

Table 2.1: Probability of emission per interaction, mean free path, and half-value layer of K and L fluorescence photons in xenon.

	$E > E_K$			$E_L < E < E_K$
	K_α	K_β	L	L
p	0.608	0.134	0.086	0.075
λ [mm atm]	204.4	290.6	5.15	5.16
HVL [mm atm]	141.7	201.4	3.57	3.58

Table 2.2: Probability of emission per interaction, mean ionization range, and multiple scatter range for K and L Auger electrons in xenon.

	$E > E_K$				$E_L < E < E_K$
	KLL	KLX	KXY	LXY	LXY
p	0.061	0.029	0.003	0.803	0.712
δ [mm atm]	1.57	2.18	2.83	0.024	0.025
R_e [mm atm]	2.62	3.64	4.71	0.040	0.041

Figure 2.5: Mean ionization range of K, L, and M photoelectrons in xenon. The numbers in the legend indicate relative probabilities. Inset: Log plot of the data.

Finally, the distance which is of interest regarding the resolution of the GMD is the mean distance δ from the point of electron ejection to the centre of the ionization produced by the electron. Following Bateman *et al.* this is approximated to be 60% of the multiple-scatter range.

It must be noted that the distribution of electron ranges is fairly broad and the shape of the distribution varies with energy. The relation between R_e and δ is therefore also expected to vary with energy. Monte Carlo codes exist based on tabulated electron-scattering cross sections (such as the code developed by Dias *et al.* [58]) which could provide a more accurate estimate of δ by calculating the spatial charge distribution produced by an energetic electron. Or, by summing the spatial charge distributions produced by all emissions following the initial x-ray absorption, it would be possible to calculate the intrinsic MTF of a xenon-based detector.

The photoelectron range is generally what limits the spatial resolution of the GMD. The values of δ for photoelectrons from the K, L, and M shells as a function of the photon energy are given in Figure 2.5. Note that the K photoelectron range is very small for photons with energy just beyond the K-shell binding energy $E_K = 34.6$ keV. This is why, even at atmospheric pressure, a xenon-based detector can provide sub-millimetre resolution for 50 to 60 kV_p x rays.

Table 2.2 provides δ and R_e for xenon Auger electrons, along with the probability of each Auger being produced per photoelectric interaction. The average L Auger ranges were computed separately for photon energies below and above E_K .

2.3 Spatial Resolution of a Xenon Detector

Using the ranges provided in the previous section, the component of the RMS (root mean square) resolution of a xenon detector due to the formation of the primary charge cloud, σ_{gas} , can be theoretically calculated. When the GMD is used with diagnostic-energy x rays, σ_{gas} is the major component of the total resolution.

The calculation is done by examining all possible outcomes to the photoelectric interactions and relaxation cascade up to a cutoff point (e.g. Figure 2.4 follows the cascade up to the L shell), determining the offset of the charge cloud centroid from the

interaction location for each outcome, and then computing the RMS offset according to the relative probability of each outcome. A model by which this can be done is described in Appendix B.

The GMD provides one dimensional readout, while the electrons and fluorescence photons can be approximated to be emitted isotropically in three dimensions from the interaction location. In order to accurately predict the RMS resolution of the GMD this must be taken into consideration.

When the offset vector $\mathbf{R}$ is at an angle ϕ to the x axis, the projected offset along the x axis is $R \cos \phi$. The resolution is determined by the RMS of $R \cos \phi$ for $\mathbf{R}$ spread uniformly over all angles (ϕ, θ) . Denoting the GMD resolution due to xenon as σ_{gas} and using the differential solid angle element $d\Omega = \sin \phi d\phi d\theta$,

$$\begin{aligned}\sigma_{\text{gas}} &= \left[\frac{1}{4\pi} \int_0^{2\pi} \int_0^\pi (R \cos \phi)^2 \sin \phi d\phi d\theta \right]^{1/2} \\ &= \left[\frac{1}{2} \int_0^\pi R^2 \cos^2 \phi \sin \phi d\phi \right]^{1/2} \\ &= R/\sqrt{3}.\end{aligned}\tag{2.16}$$

Figure 2.6 plots the error σ_{gas} in determining the x-ray interaction location. The three lines indicate the variation in resolution depending on what proportion of the xenon L fluorescence photons escape from the detector, which is determined by the pressure and the geometry of the detector.

2.4 Drift, Diffusion, and Multiplication of Charge

The drift and diffusion of ions and electrons produced in the gas microstrip detector following the absorption of a photon have an impact on both the spatial resolution and the limiting counting rate of the GMD.

Electrons and ions play very different roles in the detector. The primary ions produced when the photon is absorbed are of negligible importance to the GMD operation because they do not undergo gas multiplication, whereas the primary electrons drift to the anodes where they produce the dense avalanche of secondary electrons and ions which is collected to form the signal from the GMD. The diffusion of the

Figure 2.6: Theoretical spatial resolution of a xenon x-ray detector. This graph was produced by analytic computation from the data given in Section 2.2, using 0.6 times the electron multiple scatter range as suggested in Bateman *et al* [33] and assuming a detector with one-dimensional position readout.

primary electrons on their way to the anodes is of importance to the spatial resolution, while the drift of the secondary ions (with a mobility 1000 times smaller than the electrons) to the cathodes determines the limiting count rate of the detector.

2.4.1 Electron Drift and Diffusion

The drift velocity w of both electrons and ions is a function of the reduced field E/P , for which convenient units are $\text{V cm}^{-1} \text{atm}^{-1}$. The electron drift velocities at 20°C are given in Figure 2.7(a) for various Xe:CH₄ mixtures.

I computed the values of w and $\sigma_\perp$ in Figure 2.7 using the 1995 version of the MAGBOLTZ program written by S. Biagi [60], obtained from the author. The pure xenon and the 5% CH₄ velocities agree well with the experimental data presented in CERN 84-08 [61] except for a slight shift in E/P which could be due to differences in temperature.

It is interesting to note how strong an effect small amounts of methane have on the velocity. Changes in the slope of the w vs. E/P graph result when new modes of atomic excitation become available to the electron, and the final region of positive slope corresponds to gas multiplication where the electrons are ionizing the gas.

As the electrons drift towards the anodes, their lateral diffusion follows a Gaussian of width $\sigma_\perp$.

$$\sigma_\perp = \sqrt{2D_\perp t}. \quad (2.17)$$

where $D_\perp$ is the lateral diffusion constant and t is time. In general, it is useful to substitute $t = x/w$, where x is the drift distance, to obtain $\sigma_\perp$ as a function of x rather than of t . Figure 2.7(b) gives the diffusion after 1 cm of drift, and $\sigma_\perp$ at arbitrary x can be determined using

$$\sigma_\perp(x) = \left(\frac{x}{1 \text{ cm}}\right)^{\frac{1}{2}} \sigma_\perp(1 \text{ cm}) \quad (2.18)$$

2.4.2 The Gas Avalanche

Each primary electron will initiate an avalanche when it reaches the extremely high fields near the anodes. For our 90:10 Xe:CH₄ mixture, MAGBOLTZ predicts

Figure 2.7: (a) Electron drift velocity and (b) electron diffusion after 1 cm of drift as a function of reduced field E/P for different Xe: CH_4 mixtures at 20°C .

that gas multiplication begins when the field exceeds $10 \text{ kV cm}^{-1} \text{ atm}^{-1}$. The CH_4 is referred to as the quench gas, and adds stability to the avalanche process. The quenching mechanism is described in standard references such as Knoll (p. 168 [62]) and CERN-77 (p. 46 [54]).

The gas multiplication factor is determined from the first Townsend coefficient α , where by definition $1/\alpha$ is the mean free path of the electrons between ionizing collisions. Like the drift velocity, α is a function of the reduced field E/P . The multiplication factor M is given by

$$M = \exp \left(\int_{l_0}^{l_1} \alpha(l) dl \right) \quad (2.19)$$

where l is the path along the electric field line the electron is following, l_0 is the position at which gas multiplication begins, and l_1 is the point where the field line reaches the anode.

The multiplication factor is not exactly the same for all electrons because 1) each electron follows a different electric field line to the anodes and 2) even if all paths were identical (as they are in a cylindrical proportional counter) the number of electron-ion pairs produced per electron suffers from statistical fluctuation.

2.4.3 Ion Drift

As stated previously, the primary ions are so few in number compared to those produced in the avalanche that they have a negligible effect on the detector's behaviour. The motion of the avalanche ions, which are produced within a few μm of the anodes and subsequently drift to the cathodes or the drift plane, produces the major portion of the detector signal. The duration of the signal depends on the rate of drift.

An estimate of the ions' drift time for a 1 atm xenon GMD can be obtained as follows. Assuming an anode-cathode potential of 500 V over a distance of approximately $100 \mu\text{m}$, the average electric field over the ion's drift path is roughly 50 kV cm^{-1} . Using the data from Helm [63] (Figure 2.8) the drift velocity is $200 \mu\text{m } \mu\text{s}^{-1}$, so the ions would cover the $100 \mu\text{m}$ distance in $0.5 \mu\text{s}$. This only gives an order of magnitude

Figure 2.8: Drift velocity of Xe^+ ions in Xe as a function of E/P at 20°C. The line is a quadratic fit to the mobilities given by Helm [63].

estimate of the drift time, because 1) the electric fields are not parallel to the GMD print, 2) the ions are not all produced over the centre of the anode, nor are they collected at the centre of the cathode, and 3) not all of the ions will necessarily be Xe^+ ions.

Though the duration of the GMD signal is on the order of $0.5 \mu\text{s}$, the rise-time of the signal is tens of nanoseconds because the electric fields immediately adjacent to the anode (where the avalanche produces the ions) are far higher than 50 kV cm^{-1} . The ions move away from the anode very rapidly, traversing a large potential difference in a very short period of time. The result is that a large proportion of the signal pulse is induced in the detector over a short period of time.

A few comments should be made about Figure 2.8. The drift velocities are only given for Xe^+ in xenon, because no measurements have been made of ion drift velocities in $\text{Xe}:\text{CH}_4$ mixtures. Fortunately ion drift velocities are not as dependent on the gas mix as electron velocities, and we can assume that the drift velocity of the Xe^+ will be within approximately 10% of the pure-xenon value. However, there is a

possibility that that many (or perhaps all) of the Xe^+ ions will transfer their charge to methane atoms, resulting in a more significant change in the drift velocity. A detailed description of ion mobility in gas mixtures is provided in the book by Mason and McDaniel [64].

2.5 Charge Centroid Measurements

In a photon counting imaging system, the detector measures the location of each photon interaction. In a gas-filled detector the x-ray interaction produces a charge cloud which, in the best case, is small and symmetrically distributed about the interaction point and, in the worst case, is large and highly asymmetrical. In the former case, the best estimate of the event location is the charge centroid (the “centre of charge,” analogous to “centre of mass.”). In the latter case, the basic centroid calculation can be modified to suit the shape of the charge distribution.

2.5.1 Discrete Centroid Integration

The centroid of the charge distribution $Q(x)$ produced by a photon interaction in the detector is given by

$$\bar{x} = \frac{\int_{\ell} x Q(x) dx}{\int_{\ell} Q(x) dx}, \quad (2.20)$$

where ℓ is the spatial extent of the charge distribution $Q(x)$. The GMD anodes collect the charge cloud in discrete packets Q_i , so the GMD imaging system uses a discrete form of the centroid integral,

$$\hat{x} = a \frac{\sum_i i Q_i}{\sum_i Q_i}, \quad (2.21)$$

where a is the anode pitch.

If spatial resolution is not important, a more economical method of using the GMD than reading out the signal from each anode is to simply connect each anode channel to a discriminator and weight all channels above threshold equally. The result is the binary centroid equation,

$$\bar{x} = a \frac{n + m}{2}, \quad (2.22)$$

where anodes n through m were above threshold. The binary centroid equation cannot provide as accurate an estimate of the interaction location because the shape of the distribution is ignored. Also, the pixel mesh cannot be finer than half the anode pitch a , compared to the arbitrarily fine mesh available with Equation 2.21. The binary centroid equation is most accurate when the charge cloud has a fairly sharp drop off at its boundary. If there is significant diffusion in the detector, the drop off will be gradual and noise can easily add or subtract one anode from the centroid.

2.5.2 Effect of Charge Diffusion

The centroid calculation has little value if all of the charge is collected on a single anode. When this is the case, the resolution cannot be greater than the anode pitch. There should, therefore, be an appropriate amount of charge diffusion in the detector to ensure that the charge is spread over several anodes.

Using Equation 2.21, Figure 2.9 displays simulated profiles through images of a blank radiation field, assuming 50, 80, and 150 μm of Gaussian charge spread (the simulation is described in Appendix C). If the σ of the charge spread is too small, then the centroid calculation is strongly biased towards the anodes. Once σ is approximately 150 μm , increasing it further does not provide any significant benefit. Our detector has a 4 mm drift gap, so the ions (which are produced more-or-less uniformly over the drift volume) will, on average, drift 2 mm. According to Figure 2.7, a drift field of 0.5–5 $\text{kV cm}^{-1}\text{atm}^{-1}$ will provide >150 μm diffusion over 2 mm for Xe:CH₄ 9:1.

Unfortunately, in our GMD each charge event experiences a different amount of diffusion depending on the distance of the interaction from the print (see Figures 1.2 and 2.1). I chose to use a drift field of 1 $\text{kV cm}^{-1}\text{atm}^{-1}$ to maximize the diffusion, but according to Figure 2.7 only charge 1.1 mm or further from the print will diffuse by 150 μm or more. In the unavoidable cases where too little diffusion occurs, the events can still be spread over multiple channels if the electron ranges are sufficient but the spread is unlikely to be symmetrical. In a detector designed for high quantum efficiency, this problem would be less important because few photons would penetrate

Figure 2.9: Simulated profile through a GMD image, demonstrating the effect of varying the diffusion. The peaks always occur over the anodes, located at the tick marks.

all the way to the print.

2.5.3 Errors Arising in the Centroid Calculation

The value of σ_{gen} , the error in the centroid calculation due to the collection of the GMD signals and the subsequent generation of an image from them, can be expressed in terms of two more fundamental errors:

$$\sigma_{\text{gen}}^2 = \sigma_{\text{stat}}^2 + \sigma_{\text{elec}}^2 \quad (2.23)$$

These errors are, respectively, due to the statistical variations in the charge collected on the anodes and due to noise in the electronics. Generally σ_{gen} is much smaller than the resolution limit σ_{gas} imposed by the asymmetry of the primary charge cloud.

2.5.3.1 Statistical Variance of the Charge Cloud

The statistical variance in the number of primary electrons collected on each anode results in an error σ_{stat} in the calculated centroid. This error may be quantified as

follows.

To begin, the error in the centroid will be calculated in terms of the noise σ_{Q_k} on the charge collected on each channel k . Using standard error analysis techniques, the error resulting from the noise on a single channel is

$$\sigma_{\hat{x}k} = \left| \frac{\partial \hat{x}}{\partial Q_k} \right| \sigma_{Q_k}. \quad (2.24)$$

Taking the partial derivative of Equation 2.21 provides

$$\begin{aligned} \frac{\partial \hat{x}}{\partial Q_k} &= a \frac{k \sum_i Q_i - \sum_i i Q_i}{(\sum_i Q_i)^2} \\ &= \frac{ak - \hat{x}}{\sum_i Q_i} \end{aligned}$$

which can be substituted into Equation 2.24 to provide an expression for $\sigma_{\hat{x}k}$. Substituting $Q = \sum_i Q_i$ for the total signal and $x_k = ak$ for the positions of the anodes improves the clarity of the resulting equation:

$$\sigma_{\hat{x}k} = \left| \frac{x_k - \hat{x}}{Q} \right| \sigma_{Q_k}. \quad (2.25)$$

This equation may be restated in terms of the number of primary electrons N_{Pk} collected on each anode, and at the same time the assumption can be made that $\sigma_{N_{Pk}}^2 = N_{Pk}$ (Poisson statistics).

$$\sigma_{\hat{x}k} = \left| \frac{x_k - \hat{x}}{N_P} \right| N_{Pk}^{1/2}. \quad (2.26)$$

The errors resulting from each channel can be summed in quadrature to provide the total variance of the centroid.

$$\begin{aligned} \sigma_{\text{stat}}^2 &= \sum_k \left(\frac{x_k - \hat{x}}{N_P} \right)^2 N_{Pk} \\ &= \frac{\sum_k (x_k^2 - 2x_k \hat{x} + \hat{x}^2) N_{Pk}}{N_P^2} \\ &= \frac{1}{N_P} \left(\frac{\sum_k N_{Pk} x_k^2}{N_P} - \frac{2\hat{x} \sum_k N_{Pk} x_k}{N_P} + \hat{x}^2 \right). \end{aligned}$$

The second term in the parentheses can be replaced by $-2\hat{x}^2$ using the centroid equation (Equation 2.21). The resulting expression for σ_{stat} is

$$\sigma_{\text{stat}} = \frac{1}{N_P^{1/2}} \left(\frac{\sum_k N_{Pk} x_k^2}{N_P} - \hat{x}^2 \right)^{1/2}. \quad (2.27)$$

The second factor is the standard deviation of the spatial charge distribution collected on the anodes, which is determined by the size of the primary ionization cloud, the charge diffusion, and the anode pitch. It is important to recall that N_p (no subscript) is the total number of primary electrons, not the number collected on a particular anode.

This has an implication regarding the use of charge diffusion to smooth out the GMD response as discussed in Section 2.5.2: the error σ_{stat} is proportional to the square root of the diffusion width. The restriction is not very tight, however. A diffusion of $200 \mu\text{m}$ for a charge cloud with 800 electrons (produced by an 18 keV x ray) should result in a σ_{stat} of only $7 \mu\text{m}$.

2.5.3.2 Electronic Noise

There is noise in the digitized charge signal resulting from electronic noise in the GMD and the electronics. Following Section 2.5.3.1, the effect of this noise on the centroid error can be determined.

We start with Equation 2.25 and assume that the noise σ_{Q_k} on each channel is the same, denoting it by σ_Q . Summing the effects of all the channels, as in Section 2.5.3.1, provides

$$\sigma_{\text{elec}} = \left(\frac{\sigma_Q}{Q} \right) \left[\sum_k (x_k - \hat{x})^2 \right]^{1/2}. \quad (2.28)$$

Recall that Q refers the total signal $\sum_i Q_i$. The error is simply the ratio of the noise charge to the total charge, multiplied by a conversion factor. The conversion factor depends on the number of anodes used in the centroid calculation and on the distance of $\hat{x}$ from $(x_m + x_n)/2$, x_m and x_n denoting the positions of the first and last anodes used in the calculation. This factor is given in Table 2.3, under the conditions that the centroid is equal to $(x_m + x_n)/2$ (minimum error) or is half an anode pitch away (maximum error).

To provide a numerical example, if the electronic noise per channel is 5% of the total signal and a 4-channel centroid is used, then the centroid error will be $23 \mu\text{m}$.

Table 2.3: Electronic noise to centroid error conversion factor.

	Number of Channels Used			
	2	3	4	5
minimum [μm]	141	283	447	632
maximum [μm]	200	332	490	671

2.5.3.3 Unequal Channel Gain

The amplifiers on the anode channels drift over time, so knowledge of how far the amplification can be allowed to drift before it causes a significant error in the centroid calculation is useful.

If we limit our investigation to signals from two adjacent anodes, anodes 0 and 1, then the centroid equation simplifies to

$$\hat{x} = a \frac{Q_1}{Q_0 + Q_1}. \quad (2.29)$$

If channel 1 has a gain of b relative to channel 0, then the resulting calculated centroid will be

$$\hat{x}' = a \frac{bQ_1}{Q_0 + bQ_1} \quad (2.30)$$

and the corresponding error is

$$\begin{aligned} \Delta\hat{x} &= \hat{x}' - \hat{x} \\ &= a \frac{Q_1(Q_0 + bQ_1) - bQ_1(Q_0 + Q_1)}{(Q_0 + Q_1)(Q_0 + bQ_1)} \\ &= a \frac{(1 - b)Q_1/Q_0}{1 + (1 + b)Q_1/Q_0 + b(Q_1/Q_0)^2} \end{aligned}$$

or, rearranging Equation 2.29 to get $Q_1/Q_0 = \hat{x}/(a - \hat{x})$.

$$\Delta\hat{x} = a \frac{(1 - b)\hat{x}}{a - \hat{x} + (1 + b)\hat{x} + b\hat{x}^2/(a - \hat{x})}. \quad (2.31)$$

The largest error is expected to occur near $\hat{x} = a/2$, i.e. where

$$\Delta\hat{x} = \frac{a}{2} \frac{1 - b}{1 + b}.$$

If the gains differ by a factor of two ($b = \frac{1}{2}$ or $b = 2$) then $\Delta\hat{x}$ is only $a/6$, i.e. the error is only one-sixth the anode pitch or $33 \mu\text{m}$. As can be seen from this, channel

Figure 2.10: Simulation of the effect of unequal anode gains. Anode 5, at 800 μm , is at 90% strength and Anode 13, at 2400 μm , is at 110% strength. The charge diffusion was set to 150 μm for the simulation.

gain calibration is not tremendously important to the spatial resolution unless the gains are severely mismatched (i.e. by more than a factor of two).

However, even though the spatial resolution is not significantly affected, the error is systematic and can lead to fairly pronounced distortions in the image. In Figure 2.10, it is demonstrated that a 10% variation in gain can result in some parts of the image being 5% brighter or dimmer than the average.

Chapter 3

Imaging System

The imaging system is set up on an optical table and occupies a space of approximately $150\text{ cm} \times 50\text{ cm}$, minus the electronics which is housed primarily within an electronics rack. The system works on the principle of scanned-projection radiography (SPR), for which a fan beam is scanned line by line through the object being imaged.

3.1 GMD-SPR Apparatus

The imaging apparatus is shown in Figure 3.1. The x rays are collimated into a fan beam by an $80\text{ }\mu\text{m}$ slit before they pass through the object, and pass through a $120\text{ }\mu\text{m}$ slit immediately before entering the detector which removes radiation scattered out of the fan beam. Due to geometrical magnification and the x-ray tube focal spot size, the fan beam is $87\text{ }\mu\text{m}$ thick (full-width half maximum) with a $17\text{ }\mu\text{m}$ penumbra in the object plane and $92\text{ }\mu\text{m}$ thick with a $30\text{ }\mu\text{m}$ penumbra in the image plane. This provides approximately two-times oversampling when the usual step size of $50\text{ }\mu\text{m}$ per line (in the image plane) is used.

A detailed description of each part of the system follows. Each part is original to my research except for the pressure vessel and the electronics.

Figure 3.1: The GMD imaging system. Measurements are to the focal spot of the x-ray tube and to the drift plane of the GMD.

3.1.1 50 kV X-Ray Tube and Power Supply

The radiation source in the imaging system 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 $77\ \mu\text{m} \times 196\ \mu\text{m}$ focal spot. The smaller dimension of the focal spot is along the position readout direction of the GMD, and produces a $5\ \mu\text{m}$ penumbra in the image plane.

The tube should be capable of continuous output; however, I found that if it was run at full power for more than 20 minutes the housing became hot (50°C) and the current began to fall. When the tube was run at 75% of full power there were no problems, even after days of continuous operation.

The tube is powered by a Spellman XRM50P50X2372 50 kV power supply (Spellman High Voltage Electronic Corporation, 475 Wireless Boulevard, Hauppauge, NY 11788 USA), built into a custom controller by Ernie Neuheimer (a member of the technical staff at the Centre for Research in Particle Physics). The controller is interlocked to the doors of the x-ray room and illuminates a sign above the doors when

the x rays are on.

3.1.2 Fan-Beam Slit

The fan beam slit is made from two pieces of 1.6 mm (1/16") lead held apart by two small pieces of 80 μm foil at the edges of the slit. In order to obtain clean edges for the lead slit, the lead had been clamped between two pieces of bit steel and cut flush to the edge of the steel with a sharp utility knife. When examined under a microscope the slit was found to be of even width with nicks and burrs on the scale of 7 μm . The slit was re-cut whenever it became deformed through mishandling.

The lead slit was a temporary measure which became semi-permanent. A tungsten slit would have been better but would be fairly expensive, while a cheaper option would have been to support a tin or lead slit between thin, rigid plastic sheets for protection.

3.1.3 Object Stage

Two orthogonal micrometer stages control the position of the sample within the object plane. Because of the geometrical magnification of the system, to achieve a given displacement at the image plane the micrometers must be adjusted by that displacement divided by the geometrical magnification factor of 1.062.

The vertical stage is controlled by a Newport BM25CC motorized micrometer (Newport/Klinger Systems Center, 999 Stewart Avenue, Garden City NY 11530), which steps the sample through the fan beam. The step sizes commonly used are 47 and 94 μm (providing 50 and 100 μm displacements in the image plane).

3.1.4 LSF Slit

There are two slits which mount onto the object stage for line-spread function (LSF) measurements. The first is a 40 μm wide lead slit similar in construction to the fan beam slit, and the second is a 20 μm wide hardened steel slit. The edges of the pieces of steel used for the second slit have a bevel, which increases the apparent

width of the slit when high x-ray energies are used. At $100\text{ }\mu\text{m}$ from the slit-defining edge of the steel, the transmission is $\sim 1\%$ at 25 keV and $\sim 75\%$ at 50 keV . Because of this, the steel slit was only used below 25 kV_p .

3.1.5 Anti-Scatter Slit

A $120\text{ }\mu\text{m}$ lead slit placed 5.5 mm in front of the GMD eliminates all radiation scattered out of the fan beam. This slit is glued to a U-shaped sheet of steel which fits into the pressure window, as shown in Figure 3.2.

3.1.6 Pressure Vessel

The GMD is housed in a 6 litre cylindrical stainless-steel pressure vessel. Until the final set of xenon measurements, the vessel window was 0.36 mm of Mylar (cross-linked polyester). This window was rated to only 2 atm . A new 1.5 mm Lexan (polycarbonate) window was fabricated and installed to increase the rating of the vessel to a 6 atm pressure differential, or 7 atm absolute. With the technical assistance of Morley O'Neill, an engineer with the CRPP, I designed a window which was sunk into the vessel. This substantially reduced the amount of dead xenon in front of the GMD.

3.2 Gas Microstrip Detector

Our group's development of the GMD for imaging has evolved from earlier work in developing the GMD for particle tracking [44] [45] [46]. The construction and operation of the detectors has changed very little, except for the introduction of xenon as the fill gas and the operation of the detectors above atmospheric pressure.

3.2.1 GMD Construction

The gas microstrip plates consist of gold strips printed onto 1 mm thick S-8900 glass (Schott Glass Technologies, 400 York Avenue, Duryea, PE 18642 USA). The

Figure 3.2: Full scale drawing of the GMD and pressure window. The view is looking along the anodes, with the fan beam in the plane of the drawing. The sensitive volume is 1.5 mm off centre, as shown in the diagram, due to misalignment. All measurements are in mm.

nominal resistivity of the glass is $10^{12} \Omega \text{ cm}$, the current being carried by electrons (ions carry the current in most glasses). This slight conductivity allows ions which adhere to the glass to be neutralized, and hence allows the GMD to be operated under far higher fluence rates than would otherwise be possible. This has been widely demonstrated [65] [66].

The anode widths used were $15 \mu\text{m}$ when the detector was operated with argon and during the first set of 1 atm xenon measurements, but new prints with $7 \mu\text{m}$ anodes were used for subsequent measurements to reduce the operating voltage required to provide sufficient gain.

3.2.1.1 Print Fabrication

The GMD prints are manufactured by a photolithographic wet-etch process. The glass plate is first coated with 75 nm of nickel by evaporation. The nickel is covered in photoresist and exposed using a mask of the GMD pattern, then the exposed metal is wet etched to form the pattern. Finally, a 500 nm layer of gold is galvanically grown on top of the nickel.

The fabrication was done by VTT Electronics (P.O. Box 1101, FIN-02044 VTT

Finland) using masks manufactured by PPM Photomask Inc. (4950 Fisher Street, St. Laurent, Qué. H4T 1J6 Canada). The mask design itself was developed in our laboratory previous to my arrival.

The masks were found to be of poor quality. On the mask with 12 μm nominal anode width there were 1 μm halos around all the edges, resulting in an actual anode width of approximately 15 μm . A second mask specified to have 6 μm anodes actually had 7 μm anodes and had several defects in the form of residues jutting out from the cathodes. The scientists at VTT suggested [67], for the first set of prints, that these problems might be due to incorrect use of the pattern generator during mask manufacture. Previously PPM has produced both masks and prints for us which were of good quality.

The prints produced by VTT were of good quality, but reproduced the defects on the masks.

3.2.1.2 Inspection and Preparation

Inspection of the prints was done in a cleanroom located within the lab. Two microscopes were available, a travelling microscope with a black-and-white video display and a binocular microscope. The microscopes have similar resolution, but the video microscope provides higher magnification and greater viewing comfort.

The travelling microscope was used to catalogue the positions of defects on each print. The defects were covered with small dots of Humiseal 1B15 acrylic coating (Chase Corporation, Woodside, NY 11377 USA) to prevent electrical breakdown during detector operation, using a syringe under the binocular microscope. The ends of the anodes and cathodes were also coated.

3.2.1.3 Mounting

The prints were glued to a rigid base using small dabs of Humiseal. Connection to the readout pads on the base was done with Heat-Seal Connectors (Elform, P.O. Box 7362, Reno, NV 89510 USA). The connectors were bonded with a heat-seal press (also supplied by Elform) at 265°C by applying 7 N m (5 lb ft) of torque to the handle

of the press for 10 s. The resistance of the connections was typically $1\ \Omega$.

3.2.1.4 Geometry

The geometry of the gas microstrip detector is shown in Figure 3.2. The sensitive volume is $3.2\text{ mm} \times 5\text{ cm} \times 3.9\text{ mm}$ (width $\times$ height $\times$ depth), the width determined by the fact that 16 anodes at $200\ \mu\text{m}$ pitch are read out.

There is 3.5 mm of dead xenon in front of the detector, which could be eliminated if the vessel window were metallized to act as the drift plane. Before the Lexan window was installed, the dead xenon layer had been 24 mm thick.

The anti-scatter slit has been sunk into the vessel because it is used to define the area of irradiation during high-rate experiments, for which the x-ray tube is butted up against the front face of the vessel. Having the slit very close to the print ensures 1) that the geometrical magnification of the slit onto the GMD will be close to unity, and 2) that the blurring of the slit due to the focal spot penumbra will be slight. This is necessary because the irradiated area must be clearly defined during high-rate experiments.

3.2.2 Electronics

Figure 3.3 is a diagram of the electronics inside the pressure vessel, including a scale drawing of the GMD print itself. The following sections provide an explanation of the electronics, which were in place before I began working with the apparatus.

3.2.2.1 Anodes

The central sixteen anodes are individually grounded through $13.6\text{ k}\Omega$ resistors located on the preamplifier board. A group of eight anodes to either side of the central sixteen anodes is also grounded in order to provide a uniform drift field for the central sixteen, but are not read out. All other anodes on the print are left floating.

Figure 3.3: The electrical connections to the GMD. The dashed line represents the pressure vessel.

3.2.2.2 Cathodes

Because the cathodes are at a high voltage, they are read out through a 100 pF decoupling capacitor. The preamplifier end of the capacitor is held to ground through a 13.6 k Ω resistor. As with the anodes, only the central sixteen cathodes are read out but a group to either side is held at high voltage. Unlike the anodes, the central sixteen cathodes are read out *en masse* rather than individually.

A 1.1 M Ω resistor is placed on each cathode group to allow them to use the same high-voltage power supply without being directly coupled to one another. A resistance of tens of k Ω would actually be sufficient.

3.2.2.3 High Voltage

The high voltage for both the cathodes and drift plane is filtered through an RC circuit ($RC = 1.2$ ms) to reduce the noise from the power supplies. The RC filter resistor and an additional resistor serve to protect the GMD: if a breakdown occurs in the detector, the resistor limits the total charge the detector will draw before the large current causes the high voltage supply to trip.

The total value of the resistance between the cathodes and the high voltage supply is $12.0\text{ M}\Omega \times 2 + 1.10\text{ M}\Omega / 4 = 24.3\text{ M}\Omega \pm 1\%$, which is two or three orders of magnitude greater than required. In general this large resistance does not harm GMD operation, however it does mean that the actual voltage applied to the cathodes is $V_{\text{supply}} - I_c R_c$ where I_c is the current drawn and R_c is the resistance. For the usual dark current of $I_c = 1\text{ }\mu\text{A}$, this translates into a 24 V drop across R_c . Changes in the current due to temperature fluctuations correspond to 0–2 V, resulting in gain variations of a few percent from day to day.

The cathode and drift voltages must be ramped gradually over a period of a minute or more or the print can be damaged. This is especially true for defective prints, which suffer electrical breakdown before reaching the operating voltage if they are ramped too fast. These prints can sometimes be brought to full voltage if the ramping is done over a period of an hour or more.

3.2.3 Fill Gas

The fill gases all consisted of a noble gas and an organic quencher, mixed together in a 9:1 ratio by partial pressure. Three fill gas mixtures were used: argon:isobutane ($\text{Ar}:i\text{-C}_4\text{H}_{10}$), argon:methane ($\text{Ar}:\text{CH}_4$), and xenon:methane ($\text{Xe}:\text{CH}_4$). The $\text{Ar}:i\text{-C}_4\text{H}_{10}$ provided a faster signal and higher gain than the other two gases, which behaved very similar to each other in terms of signal and gain. Methane was chosen to replace isobutane when operation of the detector with xenon began because isobutane is known to accelerate the ageing of the GMD [68]. Dimethyl ether, which was available and is known to be a very high-performance quencher, was not used because it is both reactive and environmentally unfriendly.

The $\text{Ar}:i\text{-C}_4\text{H}_{10}$ was premixed, while the $\text{Ar}:\text{CH}_4$ and $\text{Xe}:\text{CH}_4$ were mixed in the vessel by partial pressure. The mixing was achieved as follows: the vessel and gas plumbing were evacuated to 50 mTorr, the correct amount of methane was added as read from a pressure gauge on the vessel, the plumbing was once again evacuated, and then xenon was added until the desired operating pressure was reached.

A correction factor $T/(293 \text{ K})$ was used to provide a reference temperature of 293 K. This accounted for the variation in the vessel pressure with the temperature T at the time of mixing.

3.3 Readout Electronics

A block diagram of the readout electronics is given in Figure 3.4. The data is read into a 40 MHz 80386 PC over a CAMAC interface and saved onto a networked 1 GByte disk. Typical data rates were 200–400 events s^{-1} , limited by the clock speed of the PC and the CAMAC interface software.

Figure 3.4: Simplified diagram of the output electronics, including the ADC electronics (top), MCA electronics (middle) and discriminator electronics (bottom).

3.3.1 Amplifiers

3.3.1.1 Preamplifiers

Our system uses semi-custom QPA02 current preamplifiers developed by Tom Zimmerman at Fermilab [69]. These amplifiers accept either positive or negative input and provide differential (mirrored positive and negative) output to drive a $50\ \Omega$ transmission line. There are 8 channels per chip carrier, and a fully populated 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 rise time and recovery time seen in response to a pulse from the GMD were roughly 2–3 times these values. The nominal maximum gain is $500\ \text{mV}/\mu\text{A}$ for a constant current input, and $17\ \text{mV}/\text{fC}$ for an impulse charge input. We run the amplifiers at 50–90% of full gain depending on the incident x-ray energy.

3.3.1.2 Secondary Amplifiers

The differential signal from the preamplifiers is carried via a 5 m shielded ribbon cable to a board (referred to as the receiver/discriminator or R/D board) which houses 64 Signetics NE5539 operational amplifiers (17 of which are used). These amplify the differential signal from the QPA02 into a positive unipolar signal in the range of 0–0.5 V. The quoted bandwidth for these amplifiers is $>20\ \text{MHz}$.

Because the cathode signal from the GMD has the opposite polarity to the anode signals, the two wires in the ribbon cable which carry the cathode signal are flipped just before the R/D board. This provides the correct polarity of input for the amplifiers.

Figure 3.5: The trigger circuit (top) and the realtime/livetime circuit (bottom).

3.3.2 Imaging Electronics

The signals from the amplifiers are fed into two not-entirely-separate sets of imaging electronics. One set of electronics digitizes the charge collected from each channel, allowing reconstruction of the electron cloud produced in the GMD. The second set simply applies a discrimination threshold to each channel and stores the bit pattern.

3.3.2.1 Event Trigger

The triggering system is fairly simple. If the system is not busy, an event is triggered when the cathode signal passes a threshold set by a multi-turn potentiometer. The circuit is shown in Figure 3.5. The gate generator is turned on when an event occurs, and off when the software indicates the data acquisition cycle is complete by sending a pulse via the NIM driver. The 20 ns delay ensures that the trigger pulse does not veto itself.

Figure 3.6: (a) ADC imaging electronics, and (b) discriminator imaging electronics.

Figure 3.7: The MCA built into the readout electronics. The CAMAC-qVt interface allows the computer to read the spectrum.

3.3.2.2 Realtime/Livetime Scalers

In order to allow the number of events to be corrected for the dead time of the system, there are two scalers which track both the total time (real time) and live time for each line of the image. The circuit consists of a pulser which drives two scalers, one of which (the live time scaler) is vetoed if the system is busy.

The pulser used is actually a gate generator which triggers itself through a delay line to provide 385 pulses per second. Before data acquisition, the pulsing must be initiated by unplugging and reconnecting the delay line. Additional circuitry could be added to make the pulsing initiate automatically.

3.3.2.3 Analog-to-Digital Conversion Electronics

The analog-to-digital conversion electronics are shown in Figure 3.6(a). The signal from each amplifier is of the wrong polarity and must be passed through an inverting transformer before being fed into an analog-to-digital converter (ADC). A 50 ns delay ensures that the ADC does not miss the leading edge of the signal pulses.

The P62249 inverting transformers are passive devices; they consist simply of two inductively coupled windings. I placed 50 Ω resistors on their inputs to eliminate the pulse reflections which caused ringing in the circuit. Their quoted bandwidth is 110 MHz.

Digitization is accomplished by two LeCroy 2249W integrating ADC modules, which integrate the input current over the 100 ns gate set by the trigger circuit to a maximum 11 bits of precision.

3.3.2.4 Discriminator Electronics

The anode signals are also fed into discriminators, located on the same board as the amplifiers. An EG&G CB212 coincidence buffer records the state of the discriminators each time a trigger occurs. Because of the reduced amount of data, images may be obtained approximately 16 times faster when only the discriminators and not the ADCs are used. However, image quality necessarily suffers because the centroid calculation cannot be done as accurately.

3.3.3 Spectroscopy Electronics

Radiation spectra can be collected with the GMD using three methods. First, the image data contain the charge collected on each channel for each event. These data can be histogrammed to provide channel spectra (this is provided as an option in the calibration software). Second, there is a multi-channel analyzer (MCA) patched into the imaging electronics which digitizes the full-energy signal from the cathodes. Third, an MCA card in the PC may be used to read out the GMD via an independent preamplifier.

3.3.3.1 LeCroy 3001 qVt

A LeCroy 3001 qVt multi-channel analyzer is patched into the imaging electronics as shown in Figure 3.7. We operate the qVt in q (charge integration) mode with an integration time set to 100 ns to match the imaging ADCs. Custom PC software reads the qVt via a qVt-CAMAC interface into the same file format used by the ORTEC MCA software (MAESTRO II) on the PC.

3.3.3.2 Independent GMD Readout

For higher-quality spectra and for energy resolution measurements, the QPA02 preamplifiers are replaced by an ORTEC 142PC charge preamplifier because of its low noise. A patch board allows the preamplifier to be connected to any combination of the 16 anodes or to the cathodes.

The pulses from the preamplifier are shaped by an ORTEC 450 amplifier and then sent (via 10 V positive unipolar output) to an ORTEC 916 MCA card housed in the PC. The vast majority of the spectra presented in Chapter 6 were obtained with this system.

3.4 X-Ray Shielding

I designed and largely built a shielded x-ray facility for the GMD Imaging project, the floor plan of which is shown in Figure 3.8. The shielding is 1.6 mm (1/16") lead.

Figure 3.8: Floor plan of the x-ray facility.

twice what is required as a primary shield. sandwiched between sheets of plywood. The extra thickness was used because there was no cost saving in using thinner lead. and it allows for increases in kV and workload in the facility in the future.

Chapter 4

Image Generation

The generation of images from the GMD anode signals is currently done by software rather than by dedicated electronics. Because the methods used to generate the images from the GMD signals are still under development, the flexibility provided by software is invaluable. In a practical medical imaging system, however, the image generation would have to be hard-wired to cope with the enormous number of photons which comprise a medical image.

4.1 Software Overview

The imaging software consists of four layers, though one program is shared between the second and third layers. The first layer, the data acquisition layer, is written in 16-bit FORTRAN and runs on the data acquisition PC. The second layer, which is used to calibrate the system, and the third layer, which generates the images, are also written in FORTRAN but run on a UNIX workstation. The final layer, which allows viewing and analysis of the images, is written as a set of MATLAB functions.

A flowchart of the steps between the acquisition of the data and the display of the images is shown in Figure 4.1. Each of the programs is explained briefly below, and the details of the computations done by each program are discussed in later sections.

Figure 4.1: The programs and data files involved in the image generation process.

4.1.1 Data Acquisition

The data acquisition program, NP_DAQ.FOR, was written before I began my research and no significant changes have been made to it. It serves two primary purposes: it controls the motorized micrometer which scans the object through the x-ray fan beam, and it communicates with the GMD readout electronics through a CAMAC interface. The data read by the program are output as a binary file with a '.dat' extension.

NP_DAQ has one serious bug: after exiting from the program, running it or any other program will cause the computer to hang. I believe that this problem lies in the C code which came with the motorized micrometer, specifically with the code that polls for keyboard events.

4.1.2 System Calibration

Image generation is done by two programs, calib.for and image.for. Both of these programs contain some code produced before I began working in our laboratory, but extensive modifications and additions have since been made. The use of these two programs is as follows.

First, before an image can be produced, a data set from a uniform radiation field is used to determine calibration parameters for the imaging system. Because the field is uniform, the detector does not have to be scanned as for an image acquisition. A single scan location is sufficient. The program calib.for uses this data set to determine the relative gain of each of the 16 anodes, the gain being the product of the gas gain and the amplification by the electronics. The calibration information is written into an ascii file with a '.cal' extension.

The program image.for then produces one image line from the same uniform field data. This image, which gives the relative response at each pixel location going across the detector, is written into an ascii file with a '.eff' extension.

4.1.3 Image Generation

Once the calibration files have been produced, the program `image.for` can be used to generate an image from an image data set. Each line in the image is corrected using the information in the `.eff` and `.cal` files.

The corrected image data are written to three binary files with the extension `.upc`, which are generated by 1) using the 3.4.5-channel weighted centroid calculation outlined in Section 4.4.1, 2) using the binary centroid calculation given in Section 2.5.1, and 3) integrating the charge collected on each anode for each image line. Generally, only the image produced using the first method is used.

4.1.4 Image Display

The MATLAB function `upcimage.m` reads the `.upc` file and displays the image, while an associated function, `levels.m`, adjusts the contrast of the image. Most of the images presented in Chapter 6 were produced using these functions, then saved as Postscript files and printed on a 600 dpi laser printer. These functions were written as replacements for `MPDISP`, a DOS program written by David Anderson (a previous summer student in the Physics Department) which provided essentially the same functionality.

4.2 Calibration Procedure

The calibration of the system is done in two steps, which have been mentioned earlier. They include the measurement of the relative gain of each anode channel, and the measurement of the response of the system to a uniform radiation field.

4.2.1 Anode Channel Calibration

Each of the anode channels in the GMD electronics has a different gain, due both to variations in the gas gain between anodes and due to the imaging electronics. The result of these variations is that the charge pulses from certain anodes are either

consistently stronger or weaker than the average, causing the centroid calculation to be biased either towards or away from those anodes. This results in both a distortion of fine details in the image and variations in the intensity across the image (see Section 2.5.3.3).

I have developed an iterative algorithm, coded in `calib.for`, to determine the appropriate linear calibration to apply to each channel. The following symbols will be referred to in the discussion:

Q	ADC value (proportional to the charge signal)
$N_i(Q)$	spectrum of channel i (number of events per ADC value)
α_i	relative gain of channel i
Q_{Pi}	noise pedestal (average noise ADC value)
Q_{Ai}	average ADC value between the limits $Q_{\min i}$ and $Q_{\max i}$
Q_{Ti}	noise threshold

A zero subscript on any of the above indicates the reference channel. For consistency, the reference channel is always selected as the channel with the highest gain. The goal of calibration is that all channels be corrected to match this channel.

For each channel i , the calibrated ADC value $Q_{cal i}$ of an event is equal to the uncalibrated ADC value Q_i , less the noise pedestal, and divided by the relative gain:

$$Q_{cal i} = (Q_i - Q_{Pi})/\alpha_i. \quad (4.1)$$

In order to accomplish this calibration, Q_{Pi} and α_i must be determined for each channel.

The algorithm calculates Q_{Pi} and Q_{Ai} from the anode spectra $N_i(Q)$ obtained when the GMD is exposed to a uniform radiation field. Figure 4.2 is an example spectrum for the reference channel. The value of α_i is calculated by comparing Q_{Pi} and Q_{Ai} to the values Q_{P0} and Q_{A0} determined for the reference channel:

$$\alpha_i = \frac{Q_{Ai} - Q_{Pi}}{Q_{A0} - Q_{P0}}. \quad (4.2)$$

Each of the values Q_{T0} , $Q_{\min 0}$, and $Q_{\max 0}$ shown in Figure 4.2 are given in terms of the reference spectrum, and before they are used as integration limits to calculate Q_{Pi} and Q_{Ai} they must be rescaled to match the uncalibrated spectrum. This is done

Figure 4.2: A typical single-anode spectrum, showing the quantities used in the calibration. The tall bins at the beginning and the end of the spectrum are the underflow and overflow bins of the ADC. When Q_{A0} is calculated, all of the counts past Q_{max0} are treated as if they were at Q_{max0} .

using Equation 4.2.

$$Q_{Ti} = Q_{Pi} + \alpha_i(Q_{T0} - Q_{P0}) \quad (4.3)$$

$$Q_{\min i} = Q_{Pi} + \alpha_i(Q_{\min 0} - Q_{P0}) \quad (4.4)$$

$$Q_{\max i} = Q_{Pi} + \alpha_i(Q_{\max 0} - Q_{P0}) \quad (4.5)$$

Because the rescaling depends on Q_{Pi} and α_i already being known, Q_{P0} and 1 are used respectively as initial guesses for Q_{Pi} and α_i and the values are refined by successive iteration of the two equations described below.

The noise pedestal Q_{Pi} is calculated as

$$Q_{Pi} = \frac{\int_0^{Q_{Ti}} Q \cdot N_i(Q) dQ}{\int_0^{Q_{Ti}} N_i(Q) dQ}. \quad (4.6)$$

The noise threshold Q_{T0} is set optimally when, for each channel, the fraction of noise counts which are above Q_{Ti} is approximately equal to the fraction of the total counts below Q_{Ti} which are not noise. Generally, the noise counts are well localized in the lower portion of the spectrum and both fractions can be set very close to zero.

In the case of the spectrum in Figure 4.2, the noise peak extends below the lowest non-underflow ADC value. This will result in a slight overestimation of Q_{Pi} when Equation 4.6 is applied. Ideally, the full noise peak should be visible in the ADC spectrum.

The value of Q_{Ai} is similarly calculated between $Q_{\min i}$ and $Q_{\max i}$, except that in the integral all counts past $Q_{\max i}$ are treated as if they were at $Q_{\max i}$. This adds more stability to the calibration process than if these counts were simply ignored.

$$Q_{Ai} = \frac{\int_{Q_{\min i}}^{Q_{\max i}} Q \cdot N_i(Q) dQ + \int_{Q_{\max i}}^{\infty} Q_{\max i} \cdot N_i(Q) dQ}{\int_{Q_{\min i}}^{\infty} N_i(Q) dQ}. \quad (4.7)$$

The criterion for setting $Q_{\min 0}$ is that there should be very few noise counts above $Q_{\min i}$ in any of the spectra. Also, the value of $Q_{\max i}$ must be less than ADC overflow for all spectra, which is automatically guaranteed if $Q_{\max 0}$ is set to just below the overflow ADC value in the reference spectrum.

The program calib.for calculates α_i and Q_{Pi} by repeatedly solving Equation 4.6 and Equation 4.7 until Q_{Pi} and Q_{Ai} change by less than 5% and 1% respectively compared to the previous iteration.

Figure 4.3: Relative gains α_i of the sixteen channels in the electronics. The two calibration runs were done 3.5 days apart.

Example calibration information from two 50 kV_p runs done 3.5 days apart is given in Figure 4.3. The channel gains determined for the second data set have been rescaled so that their average matches that of the first set, in order to make it easier to compare them. It can be seen that the variation between channels is quite severe. For any single data run, the gains differ from each other by as much as a factor of 3.3. There was not much variation in the gains over time, however: less than 3% over 3.5 days. I have found that calibrating the system daily is sufficient.

4.2.2 Pixel Efficiency Calibration

Calibrating the anode channels is not sufficient to provide uniform response across the image. The channels do not correspond one-to-one with the pixels across each line of the image, as is the case for most detectors used for scanned projection radiography. Rather, the signal pulses from the anode channels are used to generate a centroid $\hat{x}$ each time a photon triggers an event, and the centroid calculation provides analog position readout rather than pixel readout.

Figure 4.4: Uncorrected profile image of a blank radiation field. The tick marks on the abscissa indicate the locations of the anodes.

When the event centroids $\hat{x}_i$ are histogrammed into pixel bins, systematic errors in the centroid calculation cause some pixel locations to be favoured over others. Examples of this were provided in Figures 2.9 and 2.10 in Chapter 2, for cases of insufficient charge diffusion in the xenon and for unequal anode channel gains. Other sources of systematic error are cross talk in the electronics, and differences between the noise levels on different channels.

Figure 4.4 is a profile through an image of a uniform radiation field obtained with the GMD. The curve marked ‘theory’ is the response expected according to the σ of the spatial charge distribution in the GMD (set to be $140 \mu\text{m}$ as was measured from one of the files, see Appendix D) and the centroid calculation used (to be described in Section 4.4.1). In addition to the predicted bias error from the centroid calculation, there appears to be crosstalk between some of the anode channels.

To provide a uniform image in spite of the nonuniform response of the system, a single image line such as the one in Figure 4.4 is obtained by exposing the GMD to a uniform radiation field. An efficiency ε_j is assigned to each pixel j , which is defined

as the number of events counted in pixel j divided by the average over all pixels:

$$\varepsilon_j = N_j / \overline{N} \quad (4.8)$$

When a subsequent area image is obtained, the pixel values N_j across each line of that image are divided by the corresponding efficiencies ε_j to correct for the variations between the pixels.

This procedure was implemented in the original version of `image.for`, except that the efficiency was calculated as $N_j / N_{\max}$. I changed the efficiency to $N_j / \overline{N}$ so that the corrected pixel values would correspond more closely to the actual number of photons binned into each pixel.

4.3 Live Time Correction

In addition to the calibration of the system prior to the generation of an image, there is a correction applied to the image which accounts for the difference in the live time of the system for the acquisition of each of the lines of the scanned image. Generally the dead time of the system is very high, because we wish to obtain our image data as rapidly as possible.

Just as the pixel efficiency calibration is meant to provide uniform response across each line in the image, the live time correction is meant to provide uniform response between subsequent lines. This correction is necessary because the average dead time of the system varies between lines, due to different x-ray transmission through different sub-areas of the object.

In the program `image.for`, the pixel values in each line are divided by the ratio of the live time for that line over the average live time. The result is that the lines have been rescaled to match each other, and the corrections are fairly small so the value of each pixel is still approximately equal to the number of events binned into that pixel. An alternative, dividing by the ratio of the live time to the real time for each line, would provide a value closer to the actual number of photons which interacted at that point in the image. However, it is the number of photons counted, rather

than the number which interact, which determines the statistical noise in the image. Hence, the former is a more useful quantity.

This procedure was already implemented before I began modifying `image.for`. My only change was to scale each line to match the average live time, whereas the procedure previously scaled each line to match the highest live time.

A better option than performing a live time correction would be to modify the data acquisition program such that it spends the same amount of live time on each line of the image.

4.4 Centroid Calculation

The centroid equation (Equation 2.21) is repeated below. Recall that a is equal to the anode spacing of 200 μm .

$$\hat{x} = a \frac{\sum_i i Q_i}{\sum_i Q_i}.$$

I put considerable thought into exactly which channels i should be used in the calculation. Perhaps the simplest method is to always use the same number of channels for the calculation, most commonly 3 or 4 channels. Another method, used in previous versions of `image.for`, is to use only those channels above a set threshold. Then there are more sophisticated methods, such as the weighted methods, which provide superior results to the former two methods.

4.4.1 Weighted Centroid Methods

The centroid $\hat{x}_o$ of an odd number of channels has no error when the centroid is directly over a channel (at $x = 0$) but a large error when the centroid is halfway between channels ($x = a/2$). The opposite is true for the centroid $\hat{x}_e$ of an even number of channels. A weighted centroid $\hat{x}_w$ takes advantage of this fact by using a linear combination of $\hat{x}_o$ and $\hat{x}_e$ which varies continuously from $\hat{x}_o$ at $x = 0$ to $\hat{x}_e$ at $x = a/2$.

Figure 4.5: The calculated centroid $\hat{x}$ vs. the actual event location x using 3 channels, 4 channels, and the average of 3 and 5 channels assuming a $\sigma = 200 \mu\text{m}$ Gaussian charge cloud. The error is the vertical distance from the the solid line.

Generalizing an equation given by Lau and Pyrlik [70].

$$\hat{x}_w = \frac{a}{2} \left(\frac{\hat{x}_o}{a/2 + \text{sgn}(\hat{x}_o)(\hat{x}_o - \hat{x}_e)} \right) \quad (4.9)$$

where the channel with the maximum signal, i.e. the central channel of $\hat{x}_o$, is defined to be at a position of zero.

Lau and Pyrlik [70] suggest weighing 3 and 4 channel centroids. However, the errors on $\hat{x}_3$ and $\hat{x}_4$ do not cancel each other out, as the error in $\hat{x}_3$ is larger than that of $\hat{x}_4$ (see Figure 4.5).

I found that a vast improvement is possible if the centroid $\hat{x}_{35}$ of three channels, plus two adjacent channels weighted at half value, is used:

$$\hat{x}_{35} = a \frac{-2Q_{-2}/2 - 1Q_{-1} + 0Q_0 + 1Q_1 + 2Q_2/2}{Q_{-2}/2 + Q_{-1} + Q_0 + Q_1 + Q_2/2}. \quad (4.10)$$

The error in $\hat{x}_{35}$ cancels the error in $\hat{x}_4$ almost perfectly. The weighted centroid with $\hat{x}_e = \hat{x}_4$ and $\hat{x}_o = \hat{x}_{35}$, which I will refer to as the 3.4.5-channel weighted centroid, is the method which is currently implemented in image.for.

Figure 4.6: Simulations of various centroid methods: (a) 4-channel, (b) threshold, (c) 3.4-channel weighted, and (d) the 3.4.5-channel weighted method.

4.4.2 Comparison of Methods

Figure 4.6 simulates the calculated centroid vs. the mean of a gaussian charge distribution in an idealized GMD for different centroid methods. The solid line indicates the result when there is no noise in the system, and the dots indicate the result when there is noise on each channel. The charge cloud width used in the simulation is $\sigma = 140 \mu\text{m}$ and the RMS noise per channel is 2% of the total event charge. These parameters were extracted from an actual data run (650.dat). For the threshold method, the threshold was set to 5% of the total event charge.

The 4-channel method (a) has a region of extremely high dispersion directly over the anode and is unsuitable for imaging. The threshold method (b) has two dispersive regions. The 3.4-channel weighted method of Lau and Pyrlik (c) provides greater accuracy than the previous two methods and has no discontinuities. The 3.4.5-channel weighted method (d) has a far smaller systematic error than any of the other methods.

There is a second option, apart from developing a better centroid method, which was also considered. Because the difficulty with many of the centroid methods is that there is a large systematic error, these methods can give good results if a correction is applied to the reconstructed positions to reverse the error. For instance, a simple linear correction would remove the dispersive region in the 4-channel centroid. This route was not chosen because the magnitude of the systematic errors is highly dependent on the width of the charge cloud, which varies significantly from event to event in our system (in the simulations the width of the charge cloud was a constant).

4.5 Event Rejection

The program `image.for` rejects events which are judged to be detrimental to the image. Very little experimentation has been done to determine exactly what effect each rejection criterion has on the image, so they have been left untouched since I began modifying the program `image.for`.

4.5.1 Event Rejection Criteria

All of the following criteria depend on an anode signal threshold set in the software, which should be two or three times the noise level on the anode channels.

4.5.1.1 Ghost Events

A ghost event occurs when an event is triggered, but no anode channels are above threshold. Generally these events occur because of noise in the cathode channel, which is used to drive the trigger. Ghost events are rare unless the trigger level is set too low.

4.5.1.2 Edge Events

Edge events are those for which either anode 1 or 16 is above threshold. The reason for rejecting these events is that a portion of the charge cloud is past the edge of the GMD, and the centroid cannot therefore be accurately calculated. This reduces the effective width of the detector by $200\text{ }\mu\text{m}$ at each edge, whereas approximately $500\text{ }\mu\text{m}$ at each edge of the image would be distorted otherwise. When the image generation efficiency of the imaging system is determined according to Equation 2.5, edge events are not included in either N or in N_r (the number of rejected events) because they have no effect on the efficiency in the central area of the image.

4.5.1.3 Multiple-Peak Events

If two anode channels above threshold are separated by any number of channels below threshold, then that event is rejected. This is meant to eliminate events in which a fluorescence photon is produced and re-interacts some distance away within the detector. It was found that 1.6% to 17% of the events were rejected because they were multi-peak, the large variation resulting primarily from variations in the thresholds used for different images. The image for which only 1.6% of events were rejected used a very low threshold, and there was no noticeable deleterious effect on the image (the image is shown in Figure 6.7(b) in Chapter 6).

Rather than rejecting these events, some decision criteria could be set to determine which peak corresponds to the event location. For example, peaks with a total charge corresponding to 4 or 30 keV would have a high probability of being xenon L or K_{α} fluorescence.

4.5.1.4 Single-Anode Events

Sometimes only a single channel is above threshold. When the threshold centroid method was used (in which only those channels above threshold are used in the centroid calculation), these events had to be rejected or there would be a pixel-width peak over each anode location. When the weighted centroid method was introduced, single anode event rejection was initially removed because it was thought that it was no longer needed. However, when this was done there were prominent peaks over the anodes due to events which did not diffuse sufficiently before reaching the GMD so the rejection was reintroduced.

It was found that 1.2% to 10% of events were single-anode events in the images generated. Again, most of the difference was due to how low the threshold was set.

This rejection criterion is necessary only because of the current detector geometry, i.e. because some photons interact very close to the print and the electron cloud does not diffuse before it is collected. In a detector which is thick enough to provide a high quantum efficiency, few photons will penetrate to the print and single-anode event rejection will be unnecessary.

4.5.1.5 Diffuse Events

Events where more than five channels are above threshold are also rejected, the reason being that they correspond to events which cannot be precisely localized: e.g. events where an x-ray above the K edge interacts in the L shell, producing a very energetic photoelectron. Rejecting these events results in an improvement in the resolution, and there is not a very great loss to the efficiency.

The percentage of events which are diffuse depends heavily on both the pressure in the detector and on the x-ray energy. For 10 kV_p x rays, it was measured to be

0.2% at 1 atm and 0.0% at higher pressures. At 50 kV_p, for comparison, it was 12% at 1 atm and 0.7% at 4 atm.

Chapter 5

Experimental Methods

The properties of the GMD which were measured include the spatial resolution, the gain, the space-charge limited counting rate, and the energy resolution. Each of these parameters, except energy resolution, was measured for Xe:CH₄ 9:1 at each of 1, 2, 3 and 4 atm.

5.1 Spatial Resolution Measurements

The spatial resolution measurements were made to reflect the resolution of the GMD itself, not of the imaging system as a whole. In light of this, all quoted measurements reflect distances in the plane of the GMD and only the horizontal (GMD readout) resolution was measured. The vertical resolution is determined by the thickness of the fan beam and is therefore not a property of the GMD.

5.1.1 Criteria for Accurate Resolution Measurements

In order to accurately measure the spatial resolution of a detector, several items must be taken into consideration.

First, the system must be correctly aligned so that the parallax error is not significant. For a 3.9 mm x-ray path length through the GMD, a parallax error of less than 20 μm requires that the GMD is perpendicular to the incoming x rays to within

$\pm 0.3^\circ$. I used a square to align the front face of the pressure vessel within $\pm 0.2^\circ$.

Second, the resolution must not be limited by the x-ray tube focal spot penumbra. In our system the focal spot demagnification factor was 0.062 and the horizontal focal spot size was $77\ \mu\text{m}$, so the projection of the LSF slit onto the detector has a penumbra of only $4.8\ \mu\text{m}$.

Third, the resolution measurement should include the effects of small-scale image distortions but not large scale ones. As an example, if a pixellated detector is used to image a line-pair pattern which alternates at the pixel pitch, the image will vary from alternating black-white pixels to an even grey depending on the positioning (i.e. spatial phase) of the pattern. Similarly, a GMD image is expected to vary with spatial phase due to distortions on the scale of the anode pitch. The resolution should be taken as the average of several measurements shifted by fractions of the anode pitch to ensure a consistent result.

Fourth, sufficient photon statistics must be obtained such that they do not limit the resolution. The number of photons required depends on which method of resolution measurement is used.

5.1.2 Modulation Transfer Function Measurements

The slit response or line-spread function method was used to measure the modulation transfer function. The primary reason for this is that fewer photons are required to obtain sufficient statistics for an LSF measurement than for an edge-spread function measurement or for a set of bar-pattern measurements. This reduced the time required to obtain each resolution measurement.

5.1.2.1 Obtaining an LSF

The standard slit size used was $40\ \mu\text{m} \pm 5\ \mu\text{m}$, which is slightly magnified ($42\ \mu\text{m} \pm 5\ \mu\text{m}$ FWHM with a $5\ \mu\text{m}$ focal-spot penumbra) in the image plane. This is wide enough to have some effect on the MTF results, e.g. the MTF will be underestimated by 10% at $5\ \text{lp mm}^{-1}$ and by 25% at $8\ \text{lp mm}^{-1}$. A $20\ \mu\text{m} \pm 3\ \mu\text{m}$ slit ($26\ \mu\text{m}$ at the detector) was used at 10 and 13 kV_p. Its 10% and 25% points are $10\ \text{lp mm}^{-1}$ and

16 lp mm⁻¹ respectively.

For Ar:i-C₄H₁₀, LSF measurements were made at two or three arbitrary locations on the print, shifted to coincide, and summed. For Xe:CH₄ a standard procedure was applied where each LSF measurement consisted of four slit acquisitions exactly 50 μm apart.

5.1.2.2 Analyzing an LSF

The conversion of an LSF into an MTF curve is accomplished by

$$\text{MTF}(f) = \frac{|\mathcal{F}\{\text{LSF}(x)\}|}{|\mathcal{F}\{\text{LSF}(x)\}|_{f=0}} \quad (5.1)$$

where $\mathcal{F}\{\}$ denotes the Fourier transform. The general procedure applied to each LSF was as follows:

First, all pixels outside of the LSF peak were set to zero. There was never a significant background, but there were a few counts sprinkled outside of the peak believed to be due to noise in the electronics. Then, the field of view was extended with zeros to 256 pixels if it was not that size already. This large field of view provides an appropriately small distance between the sample points in the MTF. Finally, the Fourier transform of the data was calculated, the absolute value taken, and the result was rescaled to 1 at zero to provide the MTF. At times the resulting MTF fell to zero but later rose again due to statistical noise in the LSF. In these cases, everything after the zero was set to zero.

5.1.3 Resolution Test Patterns

Two resolution test patterns were available, a parallel bar pattern and a star pattern (see Figure 5.1). Neither of these patterns was ever imaged in its entirety because our imaging system has only a 2.6 mm wide field of view. Instead, a 2.6 mm wide swath was imaged over some region of interest.

Figure 5.1: The bar and star test patterns.

5.1.3.1 Bar Pattern

When the bar pattern was used, one set of three bars was placed at an angle of approximately 20° from the vertical in the centre of the field of view. One or two millimetres of the pattern were scanned in $100\ \mu\text{m}$ steps, using a horizontal pixel size of $25\text{--}50\ \mu\text{m}$. The lp/mm labels on the pattern represent the line density in the object plane; these numbers were divided by the system magnification factor to provide the line density in the image plane.

5.1.3.2 Star Pattern

For the star pattern, an image a few mm along one of the wedges samples a range of line densities. The line density in the image can be determined by two methods. In the first method, landmarks are placed at points on the star pattern which are calculated to have a given line density. These landmarks, e.g. pieces of copper tape, can be used to calibrate the image.

The second method, which was the method used to calibrate the images presented

in the next chapter, was the following. The image was printed at $20\times$ magnification along with a millimetre scale representing distances in the plane of the GMD. Construction lines were drawn with a pencil along the central bright line in the image and also along the fifth bright line to either side. The distance across these ten line pairs was measured and hence the line density in the image was calculated.

5.2 Energy Spectroscopy

Energy spectra from the GMD were measured using both an ORTEC 142PC charge preamplifier and using the QPA02 preamplifiers built into the readout electronics. The 142PC was preferred because it guaranteed better linearity and lower noise than the QPA02 preamplifiers, which were designed to provide a fast signal rather than to be used for spectroscopy.

5.2.1 EG&G ORTEC 142PC

The 142PC was used with an ORTEC 450 amplifier set to unipolar output. A shaping time of $1\ \mu\text{s}$ was used for all spectra. Where possible, the energy scale of the spectra was calibrated using either the 5.9 keV peak from an ^{55}Fe source or using the 17.7 keV and 59.6 keV peaks from an ^{241}Am source.

When radioactive sources were not available, the 8.39 keV or the 9.70 keV tungsten emission lines from the x-ray tube were used instead. The emission peaks sit on top of a bremsstrahlung background and are poorly separated, so the MCA cannot be calibrated as accurately with them as with the isotope lines.

5.2.2 QPA02

The primary advantage of doing spectroscopy with the QPA02 preamplifiers is that the MCA used to collect the spectra from them is embedded in the readout electronics. Spectra were generally not obtained from the QPA02 for the purpose of energy spectroscopy, but rather to measure the rate-dependent gain of the system (as described in Section 5.3).

5.2.3 Pinhole Spectra vs. Slit Spectra

It is useful to separate spectroscopy measurement into two categories: pinhole measurements and slit measurements. In the former, the radiation is collimated into a 0.5 mm diameter pencil beam which is aimed at the centre of the sensitive area of the GMD. This ensures that electrons which are put into motion in the sensitive area also stop within the sensitive area, i.e. the full energy transferred to the detector by the photon is collected less the energy of escaping fluorescence photons. A few electrons will unavoidably cross the drift plane, leading to slight spectral distortion.

In slit measurements, the entire sensitive width and at least 1 mm beyond is irradiated. As a result, many electrons produced near the boundary of the sensitive area will cross to the other side. This leakage of electrons occurs in both directions across the boundary.

While pinhole measurements aim to accurately measure the incident spectrum, slit measurements aim to measure the spectrum of energy deposited over a specific sub-area of the total irradiated area of the GMD. The reason a slit is used, rather than the full area of the GMD being irradiated, is that 1) the gain is not uniform at the ends of the strips and 2) there were defects on the print a few mm away from the area defined by the slit. The primary instances where slit measurements are used are rate measurements, where the charge deposited per unit area of the print must be accurately known. The charge per unit area is calculated as the average charge per anode, divided by 200 μm .

In the limit of low photon energy, where the electron ranges are small, pinhole and slit measurements provide nearly equivalent spectra. Because of this, low-energy spectra were obtained with a slit to reduce the time required to collect the spectra.

5.2.4 Energy Resolution Measurements

The energy resolution was measured under two conditions: Ar:*i*-C₄H₁₀ at 2 atm and Xe:CH₄ at 1 atm. The energy resolution was determined by measuring the full-width half-maximum of the 5.9 keV ⁵⁵Fe peak for Ar:*i*-C₄H₁₀, and of the 17.7 and 59.6 keV ²⁴¹Am peaks for Xe:CH₄.

5.3 Gain Measurements

The gain M of a charge detector such as the GMD is the ratio of the avalanche charge to the primary charge produced by the radiation. Gain measurements fall into three categories: relative, semi-absolute, and absolute. Relative gain measurements may only be compared to other measurements taken at the same time. For semi-absolute measurements, the amplifier and MCA are calibrated using a test input to provide gain values which can be compared to values taken at other amplifier and MCA settings, but not with different detectors. Finally, absolute measurements involve making an absolute measurement of the charge (or current) produced in the detector in response to a known rate of energy deposition by the radiation.

5.3.1 Relative and Semi-Absolute Gain

The easiest method for measuring the gain is to irradiate the GMD with a spectrum containing one or more identifiable spectral lines, and to capture the absorption spectrum from the GMD using a multi-channel analyzer. Each peak in the spectrum corresponds to a specific amount of charge q deposited in the GMD, according to

$$q = eE/W, \quad (5.2)$$

where E is the energy of the line and W is average energy required to liberate an ion pair. If the amplifiers used to read out the detector are linear, then the MCA channel number C is related to the charge Q produced in the detector by

$$C = C_0 + AQ. \quad (5.3)$$

Combining these two equations provides an expression for the gain M :

$$\begin{aligned} M &= Q/q \\ &= \frac{W}{eEA}(C - C_0). \end{aligned} \quad (5.4)$$

For relative measurements, C_0 was usually determined by calibrating an MCA spectrum from two or more known spectral lines. If only one spectral line is present,

it may be possible to determine C_0 using the noise pedestal. The noise pedestal is the average signal obtained if the MCA gate is triggered at regular intervals while the detector is not being irradiated, and appears as a sharp peak at C_0 . This method can only be used if the MCA is linear at low channel numbers, as is the case for the LeCroy 3001 qVt but not for the ORTEC 916 MCA.

Ideally both C_0 and A could be measured by calibrating the system with a pulser, which injects known amounts of charge Q' onto the 142PC via a nominal 1 pF test capacitor. Because the charge Q' collected by the 142PC is less than the total charge Q produced in the GMD, the measured semi-absolute gain M' will be smaller than the absolute gain M .

5.3.2 Absolute Gain

To determine the true absolute gain, the detector was irradiated at a moderately high rate through a pinhole and the resulting detector current was measured (the sum of the currents through the drift and cathode power supplies, less the dark current). The rate chosen was just below the rate at which the detector gain began to fall due to space charge effects. The gain was calculated by dividing the detector current by the rate of charge production from interacting x rays, which is equal to the detected count rate times the average charge deposited per x ray (calculated from the average absorbed energy per event and the W value of xenon). The pinhole was used to ensure that all the charge was collected on the central sixteen anodes (which are connected to the counter) and not on the anode groups to either side (which are not connected to the counter).

This absolute gain measurement was compared with a semi-absolute gain measurement obtained under the same conditions, except a lower rate, to determine the factor to convert M' to M . This factor was determined to be 3.03 for our $7\ \mu\text{m}$ anode print when read out with the 142PC (serial number 000018) preamplifier.

5.4 Rate Tests

The effect of the high space-charge density resulting from high-rate operation of the GMD is the reduction of the gain in the GMD. Two methods of measuring the relative gain, detector current and MCA peak position, were used to measure the drop in gain at high x-ray fluence rates. The MCA method does not provide an accurate measurement of the drop in gain because pulse pile up at high rates distorts the energy peaks used to measure the gain. The detector current method, however, provides an accurate assessment of the drop in gain due to space charge effects alone. Rate measurements were done using both methods for Xe:CH₄ at 1–4 atm.

The geometry for the rate measurements was as follows: The tube focal spot was 105 mm from the GMD drift plane, and irradiated the GMD through a 120 μ m slit 5.5 mm from the drift plane. The tube voltage was 30 kV_p and no filtration was used.

5.4.1 Detector Current Method

To measure the gain vs. fluence rate using the detector current, the detected counting rate and the current from both the drift plane and the cathodes (as measured from their respective power supplies) were recorded as functions of the x-ray tube current. After each data point was recorded, the radiation was turned off and the dark current in the detector was measured. The dark current drifted by less than 1% over any one set of measurements.

Several steps were taken to analyze the data. First, the count rate was corrected for the trigger reset time τ , which is the time required for a pulse to drop back below the trigger threshold so that the counter can accept another pulse. The actual pulse rate r is related to the counted rate r_c by

$$r = r_c(1 + \mu) \quad (5.5)$$

where $\mu = r\tau$ is the average number of pulses which occur during the reset time. Rewriting Equation 5.5,

$$1/r = 1/r_c - \tau. \quad (5.6)$$

The pulse rate r and the x-ray emission current I are related by a proportionality constant A , so equivalently

$$1/I = A/r_c - A\tau. \quad (5.7)$$

A linear fit to $1/I$ vs. $1/r_c$ was used to determine τ . Hence, each measured r_c was converted into a pulse rate r , and dividing r by the irradiated area provided the photon fluence rate ϕ .

The detector current, less the dark current, is proportional to ϕ at low fluence rates but subproportional at high fluence rates. To measure the effect, the first few points in the current vs. fluence rate plot (for which the current is expected to be proportional to the fluence rate) were fit to a straight line. The relative gain of higher points was calculated as the ratio of the measured current to the current predicted by the line.

A correction had to be added due to the large protection resistance in series with the cathodes. The actual voltage applied to the cathodes is $V_c = V_{\text{supply}} - I_c R_c$ where I_c is cathode current and R_c is the resistance. When I_c rises in response to an increase in the fluence rate, the applied cathode voltage and hence the detector gain decreases. The measured gain vs. cathode voltage characteristics (Section 5.3) were used to correct for the gain loss due to this effect.

5.4.2 Peak Method

Using peak position to measure the gain drop was more straightforward than using the detector current. An MCA (LeCroy 3001 qVt) with a 100 ns integration gate was used to measure the signal spectrum for each tube current setting. With the radiation turned off, the MCA gate was triggered off a pulser to place a noise pedestal peak in one of the spectra. This peak was used as the zero of the MCA. The change in the channel number of the 9.70 keV tungsten line was used as a measure of the change in the gain.

In order to estimate the rate ability of a hypothetical system more highly optimized than ours, the integration time was reduced to 70 ns and a 0.5 mm pinhole was used to limit the irradiated area to just 3 anodes (an optimized readout scheme would

check for coincidence only between neighboring anodes, not over the entire detector). The reduced integration time and smaller number of anodes decreases the frequency of pulse pile up. This measurement was done only at 1 and 2 atm.

The gain was corrected for the voltage drop across the protection resistor as for the detector current method.

Chapter 6

Experimental Results

This chapter presents measurements of the spatial resolution, gas gain, space-charge limited counting rate, and energy resolution of the GMD. The final section in the chapter presents some images which have been obtained with our system.

6.1 Spatial Resolution

The spatial resolution results are given in terms of the spatial frequency in the plane of the GMD. The MTF curves for which the maximum x-ray energy was below the xenon K-edge are shaped similarly enough that the following rule can be applied: the frequency at which the MTF crosses 0.05 is approximately $1/(2\sigma)$ where σ is obtained by fitting a Gaussian $\exp(-\frac{1}{2}(x/\sigma)^2)$ to the line spread function. This approximation holds to a lesser degree for spectra which extend above the K-edge.

6.1.1 MTF Measurements

All of the MTF curves presented in this section were obtained from LSF measurements as discussed in Section 5.1.2. A horizontal line is provided on each plot to indicate where the MTF crosses 0.05, because spatial frequencies beyond this point are unlikely to be resolved. Table 6.1 gives the frequency at which $\text{MTF}(f)$ crosses 0.05 for each measurement.

Table 6.1: Spatial frequency [lp mm^{-1}] at which $\text{MTF}(f)$ crosses 0.05.

tube kV_p and filtration		Xe: CH_4				Ar: $i\text{-C}_4\text{H}_{10}$	
		1 atm	2 atm	3 atm	4 atm	1 atm	2 atm
10 kV_p	0.25 mm Be	7.2	11.8	—	—	4.6	7.0
13 kV_p	0.25 mm Be	—	—	13.0	14.0	—	—
20 kV_p	0.5 mm Al	4.4	—	—	—	—	—
30 kV_p	1.2 mm Al	3.1	3.8	5.4	6.2	—	—
40 kV_p	1.7 mm Al	5.0	—	—	—	—	—
50 kV_p	2.4 mm Al	5.5	6.7	8.4	7.0 (8.5*)	—	—

*With 72.2 mm Lucite filtration.

6.1.1.1 MTF vs. Energy

The MTF curves for the GMD are presented for increasing x-ray energy in Figure 6.1. all of the measurements being done with xenon at 1 atm. The resolution of the system falls with increasing energy up to 30 kV_p , as is expected from the increasing range of the L-shell photoelectron. Once the kV_p passes the xenon K-edge at 35 keV, the tail of the MTF curve begins to rise as more x-rays convert in the K shell rather than the L shell, producing short-range K photoelectrons rather than longer-range L photoelectrons. The resolution is expected to eventually peak, and then begin to fall again as the K-photoelectron range increases.

Because our detector is only 4 mm deep, the quantum efficiency is approximately proportional to the total x-ray attenuation coefficient μ . Hence, the probability of a photon just above the K edge interacting in the detector is approximately a factor of five higher than that of a photon just below the K edge. Because the K photoelectron range is far shorter than the L photoelectron range, this results in an exaggeration of the resolution at 50 kV_p compared to what would be obtained with a greater xenon depth.

6.1.1.2 MTF vs. Gas Pressure

Figures 6.2–6.4 demonstrate the increase in resolution with gas pressure at different energies. Because the electron ranges are inversely proportional to the pressure, the resolution is expected to increase roughly proportional to the pressure until some

cutoff determined by the accuracy of the charge readout from the GMD.

Figure 6.2 shows the results at 10 kV_p for both argon and xenon. The resolution with argon is 0.6 times the resolution with xenon, whereas a naive prediction based on the ratio of the electron stopping powers dE/dx (2.44 keV cm⁻¹ atm⁻¹ for argon and 6.76 keV cm⁻¹ atm⁻¹ for xenon [54]) would give 0.3. However, the Auger electrons produced in xenon will have a higher energy and longer ranges than those produced in argon and this could account for the difference.

The resolution increases roughly proportional to the pressure from 1 atm Xe to 2 atm Xe, but appears to asymptotically approach a maximum. This maximum resolution (defined by the 3 and 4 atm MTF curves) could be the limit determined by the noise in the channel signals used to calculate the event centroids, but other possible explanations will be offered in Section 6.1.3.

Figure 6.3 shows the MTF at different pressures for 30 kV_p x rays. The resolution is sub-proportional to the pressure, and the resolution at 2 atm in particular is much worse than double the resolution at 1 atm. The reason is that the mean energy of the photons absorbed by the detector increases as the pressure $\times$ depth product of the detector increases. The mechanism is similar to that of beam hardening, except that one is concerned with the absorbed photons rather than the transmitted photons.

For the 50 kV_p spectrum, the resolution increases by only 50% going from 1 to 3 atm and then decreases going from 3 to 4 atm (see Figure 6.4). This is due in part to the increasing pressure $\times$ depth product as described for the 30 kV_p data. However, there is another effect present as well: the 3.5 mm layer of dead xenon in front of the GMD acts as a K-edge filter, attenuating those photons which provide the highest spatial resolution. The effect of this K-edge filtration on the absorbed energy spectrum will be shown in Section 6.4.3.

Figure 6.5 demonstrates what happens when a few centimetres of lucite filtration are used to increase the proportion of x rays above the K edge. The MTF(f) = 0.05 frequency increases from 7.0 to 8.5 lp mm⁻¹.

Although the MTF data demonstrate that the resolution of the GMD is very good at 50 kV_p, the MTF drops off very rapidly at low spatial frequencies. Such an MTF would allow fine details to be seen, e.g. fracture lines in bones, but the MTF might

Figure 6.1: MTF for different x-ray spectra with 3.9 mm of xenon at 1 atm.

Figure 6.2: MTF at different pressures for low kV_p beams. The curves at 1 and 2 atm were obtained for $10\text{ kV}_p + 0.25\text{ mm Be}$ filtration, while the curves at 3 and 4 atm were obtained for $13\text{ kV}_p + 0.25\text{ mm Be}$.

Figure 6.3: MTF at different xenon pressures for 30 kV_p + 1.2 mm Al filtration.

Figure 6.4: MTF at different xenon pressures for 50 kV_p + 2.4 mm Al filtration.

Figure 6.5: Improvement of MTF with increased filtration.

not provide good visibility for low contrast details on the order of 1 mm across.

6.1.2 Test Pattern Images

Bar pattern and star pattern images were obtained for a subset of the x-ray spectra and gas pressures for which MTF curves have been presented. It was from viewing these images that it was decided that the spatial frequency at which the MTF crosses 0.05 was a reasonable indicator of the maximum resolution of the system.

The lp mm^{-1} values given with the images are those in the image plane, rather than in the object plane. To convert to the actual lp mm^{-1} quoted on the test pattern, the given values must be divided by the system magnification factor of 1.062.

6.1.2.1 Notes on Image Display

There are four numbers to the right of each image which indicate how the image data has been matched to the displayed grey values (see Figure 6.6). The top and bottom numbers give the maximum and minimum pixel values present in the image

data, while the central two numbers indicate the pixel values which have been matched to the brightest and darkest grey levels (white and black). A grey scale is printed on the right edge of each figure to make it possible to estimate the pixel values from the grey levels. For all of the images, the pixel values are approximately equal to the number of recorded x-ray interactions per pixel.

For both the bar and star pattern images, the minimum pixel value is generally above zero because there is some transmission of x rays through the lead of the patterns.

6.1.2.2 Bar Pattern Images

Example bar pattern images are shown in Figure 6.6. The images on the top row were obtained at 10 kV_p, and represent $MTF(f) \approx 0.15$ (good contrast). The second row of images were all obtained at 50 kV_p with xenon at 1 atm, and show decreasing visibility with increasing line density. The visibility cutoff is predicted to occur at around 5.5 lp mm⁻¹ from the MTF curve.

6.1.2.3 Star Pattern Images

The star pattern images in Figure 6.7 show the highest resolutions attained at 13, 30 and 50 kV_p. The 13 kV_p image (a) extends to the very end of the star wedge, the lines still being clearly visible at 11 lp mm⁻¹. The slight brightening of the last row is due to the cut in the lead across the end of the pattern.

At 30 kV_p (b) the visibility is good at 6.5 lp mm⁻¹ and continues to perhaps 7.0 lp mm⁻¹, compared to the 6.3 lp mm⁻¹ predicted by $MTF(f) = 0.05$. The MTF at these frequencies is expected to be 1.15–1.20 times the measured MTF, because the width of the slit used to measure the MTF was 40 μm wide.

The drop off of the 50 kV_p MTF is very gradual at high spatial frequencies, and the visibility of the lines in Figure 6.7(c) correspondingly decreases very gradually. The visibility is still reasonable at 8.2 lp mm⁻¹, compared to 8.5 lp mm⁻¹ at which the MTF crosses 0.05.

The two circles in the image and the white patch in between them are an artifact

Figure 6.6: Bar pattern images. The top row of images is for argon and xenon at 10 kV_p, and the bottom row of images is for xenon at 50 kV_p.

Figure 6.7: Star pattern images for different x-ray energies.

which appears to be due to one anode channel temporarily becoming much stronger than usual. The anode channel in question, number 9, is generally only one-third the strength of the strongest channel before calibration. It is possible that the weakness of this channel was due to a poor electrical connection which temporarily fixed itself.

6.1.3 Comparison to Theory

In Chapter 2, the theoretical root mean square deviation of the calculated centroid from the photon interaction location was given. The total RMS deviation was separated into three terms: 1) the deviation of the primary charge cloud centroid (projected along the GMD readout direction) from the x-ray interaction location, 2) the centroid error due to the primary electron statistics and the diffusion, and 3) the centroid error due to electronics noise.

In this section, the theoretical RMS deviation σ_{gas} due to (1) is compared to the RMS width σ_x of the measured line-spread functions. Note that $1/(2\sigma_x)$ does not directly indicate the highest spatial frequency which can be imaged, which depends on the shape of the MTF curve. In order to predict the limiting spatial resolution accurately, the width and shape of the line-spread function would have to be predicted and the theoretical MTF calculated from it.

The theoretical treatment of the electron and fluorescence photon ranges in xenon given in Section 2.2.3 resulted in the calculation of σ_{gas} , which was given in Figure 2.6. Figure 6.8 superimposes the measured σ_x values on the σ_{gas} plot, both being given in units of mm atm. The abscissa values for the measured values are the mean energy of the incident spectrum: 8 keV for 10 kV_p, 10 for 13 kV_p, 16 for 20 kV_p, 21 for 30 kV_p, 27 for 40 kV_p, and 32 for 50 kV_p. The mean energy was calculated from theoretical spectra for 30 and 50 kV_p (taken from Birch and Marshall [56]), and estimated for the other spectra.

At 10 and 13 kV_p, σ_x is within the possible range of σ_{gas} for all pressures. The value of σ_x increases with pressure, indicating either that 1) as the pressure increases fewer L fluorescence photons escape, or 2) at the higher pressures the error due to the electronics noise and primary electron statistics becomes dominant.

Figure 6.8: Comparison of the measured σ_x with the theoretical σ_{gas} .

Looking just at the 1 atm data (the open circles), there is good agreement with theory until 40 and 50 kV_p. The 40 and 50 kV_p points are off for two reasons. First, the quantum efficiency of the detector is much higher above than below the K edge, so the values of σ_x are expected to match roughly with the value of σ_{gas} past the K edge. Second, in the image generation process any events with more than five anode signals above threshold are rejected, resulting in an improvement of the resolution. For the 40 and 50 kV_p data respectively, 14.6% and 11.7% of events were rejected for this reason. Because the RMS calculation weighs poor resolution events more heavily than good resolution events (because the resolution is squared before the average is taken), this could account for a significant difference in σ_x .

For comparison, for the 50 kV_p data at 2, 3 and 4 atm the event rejection due to this criterion was 6.3%, 2.1%, and 0.7% respectively. This could explain the increase of σ_x with pressure. Another reason for the increase could be the K-edge filtration of the beam by the dead layer of xenon, which was mentioned in reference to the MTF curves in Section 6.1.1.2. At 3 and 4 atm, the resolution agrees fairly well with theory

given that approximately equal fractions of the absorbed photons will be above and below the K edge.

There is also a steady increase in σ_x with pressure at 30 kV_p, which could be partially due to the event rejection discussed above (though at 50 kV_p the effect was accentuated because of the sharp distinction between high-resolution, K-photoelectron events and low-resolution, L-photoelectron events). As well, there will be hardening of the absorption spectrum as was mentioned in reference to the MTF in Section 6.1.1.2. The absorbed energy spectrum was measured for each of these data points, and will be presented in Section 6.4.3.

6.1.3.1 Theoretical Error Due to Signal Noise

There is enough information in the '.dat' files for the line-spread function measurements to calculate what the electronic noise and the width of the collected charge distribution were, and hence calculate σ_{stat} and σ_{elec} as given by Equations 2.27 and 2.28. This information was extracted from the first 41 events of the 3 atm, 13 kV_p LSF data set (650.dat). The LSF and the collected charge distribution determined from these data are shown in Figure 6.9.

The noise in the electronics was determined to be $\sigma_Q = 38$ ADC units by calculating the RMS variation for each of eight anode channels which were not being irradiated, and then averaging the eight values. Similarly, the average total signal Q per event was determined to be $Q = 1867$ ADC units by averaging the sum of six irradiated anodes. Using Equation 2.28, the centroid error due to the electronics noise is expected to be

$$\sigma_{\text{elec}} = \frac{38}{1867}(469 \mu\text{m}) = 9.5 \mu\text{m}.$$

From the same data file, the standard deviation σ of the collected charge distribution was found to be $157 \mu\text{m}$. The average energy of the 13 kV_p spectrum is 10 keV, so the number of primary electrons in the charge cloud is $N_p = (10^4 \text{ eV})/(22 \text{ eV/ion pair}) = 455$. Using Equation 2.27, the error from the primary electron statistics is

$$\sigma_{\text{stat}} = \frac{157 \mu\text{m}}{\sqrt{455}} = 7.4 \mu\text{m}.$$

Figure 6.9: Line-spread function (solid line) and collected charge distribution (dashed line) at 13 kV_p for xenon at 3 atm. The value of σ is the average standard deviation of the collected charge distribution, and the value of σ_x the RMS deviation of the LSF from zero.

The total predicted error due to these two effects is

$$\left[(9.5)^2 + (7.4)^2\right]^{1/2} = 12 \mu\text{m}.$$

This is very small, only a very minor portion of the total $\sigma_x = 48 \mu\text{m}$ of the LSF peak. In fact, this is even less than the error expected from the $20 \mu\text{m}$ width of the LSF slit.

If σ_{elec} and σ_{stat} are the two major components of the RMS resolution apart from σ_{gas} (i.e. if there are no major components unaccounted for), then the resolution of the GMD could be improved significantly by further increasing the pressure. According to the σ_{gas} plot (see Figure 6.8), the resolution at low energies is determined almost completely by the L fluorescence photons: hence, the resolution could have been the same for 3 and 4 atm ($48 \mu\text{m}$ RMS vs. $46 \mu\text{m}$ RMS) not because the maximum resolution had been reached, but because at 4 atm fewer L fluorescence photons were escaping from the detector.

6.2 Detector Gain

6.2.1 Gain Variation with Pressure

Gain vs. cathode voltage curves are shown for various pressures in Figure 6.10. The quoted cathode voltage V_c is the reading from the high voltage power supply, less the calculated voltage drop $I_c R_c$ over the resistance between the cathodes and the power supply. The drift field was 1.3 kV cm^{-1} at 1 atm, and $1.0 \text{ kV cm}^{-1} \text{ atm}^{-1}$ at all other pressures.

The gains for Ar:CH₄ and Xe:CH₄ are very similar, though the gain vs. V_c curves have different slopes. The electron transport properties of counting gases are determined largely by the quencher used, so this might be expected. The data of Budtz-Jorgensen *et al* [71] indicate a gain 1.5 to 2.0 times higher for Xe:CH₄ than for Ar:CH₄, for Ar:CH₄ gains in the range of 5×10^2 to 2×10^3 .

At pressures of 1 atm to 3 atm, the value of V_c required to achieve a gain of 500 increased by 91 V per atm of pressure. From 3 atm to 4 atm, the increase was only

Figure 6.10: Gas gain vs. V_c for a GMD with $7 \mu\text{m}$ anodes.

Figure 6.11: Gas gain vs. V_d for GMD with $7 \mu\text{m}$ anodes and a 3.9 mm drift gap with V_c set at -442 V. Note the loss of gain when V_d is less than V_c .

Table 6.2: Gain curve fit parameters.

	a	b [V ⁻¹]
1 atm Ar:CH ₄	0.0801	0.0192
1 atm Xe:CH ₄	0.1415	0.0177
2 atm Xe:CH ₄	0.0663	0.0161
3 atm Xe:CH ₄	0.0209	0.0157
4 atm Xe:CH ₄	0.0453	0.0135

43 V, which suggested that at 4 atm a mixing error was made and there was less methane in the mixture than there should have been. Whether this actually was the cause has not been ascertained, but the rate data at 4 atm, to be presented later, confirm that there was a change in the properties of the detector which are not simply the result of an increase in pressure.

The gain vs. cathode voltage curves were fit to the function $M = a \exp(bV_c)$, the results being given in Table 6.2. The error on a is $\pm 5.5\%$, determined from the uncertainty in the conversion from relative to absolute gain, and the error on b is ± 0.005 V⁻¹, determined from the uncertainty on the value of the cathode protection resistance.

The gains at 1, 2 and 3 atm are approximately half the gains measured by Shekhtman [72] using the same gas mix for a GMD with $3 \mu\text{m} \times 1 \mu\text{m}$ anodes and $60 \mu\text{m} \times 1 \mu\text{m}$ cathodes. Our GMD, for comparison, has $7 \mu\text{m} \times 0.5 \mu\text{m}$ anodes and $90 \mu\text{m} \times 0.5 \mu\text{m}$ cathodes.

6.2.2 Gain vs. Drift Voltage

The variation of the gain with the drift voltage V_d was roughly linear for $V_d > V_c$ (Figure 6.11). The gain increased by only 60% in response to a 400% increase in V_d .

6.3 Counting Rate Ability

The rate curves presented in this section give the relative gain as a function of the detected fluence rate (as determined from the signal rate from the GMD). For

Table 6.3: Fluence rate [$\text{mm}^{-2}\text{s}^{-1}$] at which the gain falls by 10%.

	1 atm	2 atm	3 atm	4 atm
Detector Current	$>3 \times 10^7$	8×10^6	2×10^6	$>2 \times 10^6$
MCA. Pinhole	1.2×10^7	3×10^6	—	—
MCA. Slit	3×10^6	1.4×10^6	9×10^5	1.3×10^6

all curves, the gain has been normalized to one for the average of the first few data points.

The GMD was irradiated through a $120 \mu\text{m}$ slit during the rate tests, to mimic the way that the GMD is used in our scanned projection radiography system. The results, therefore, cannot be directly compared to measurements by other groups who irradiated a large area of their GMD. The detected fluence rates at which the gain fell by 10%, using three different methods of measurement, are given in Table 6.3. To make comparison with other rate curves possible, the average charge produced in the detector per event was 41, 41, 43, and 33 fC respectively at 1, 2, 3, and 4 atm.

6.3.1 Gain via Detector Current

The detector current is the most direct indication of the rate of charge production in the detector, and hence provides the most direct measurement of the drop in detector gain due to space-charge effects.

Data for 1, 2, and 3 atm Xe:CH₄ are shown in Figure 6.12. The error bars represent the sum of 1) the random error from the current measurement, 2) the systematic error from the fit of the first few points of the current vs. fluence rate characteristic to a straight line, and 3) the systematic error from the correction of gain drop due to the protection resistor. The data for 4 atm will be presented later in this section because the parameters for the measurement were different from the other pressures.

A reasonable definition of the limiting counting rate is the rate at which the gain drops by 10%, i.e. the rate at which variations in the energy resolution and spatial resolution of the detector are likely to occur. The limiting counting rates determined from Figure 6.12 are given in the Table 6.3.

Babichev *et al* [1] obtained limiting rates of 8×10^5 , 5×10^5 , 4×10^5 , and 3×10^5 pho-

tons $\text{s}^{-1}\text{mm}^{-2}$ for 1–4 atm respectively. According to their results, the limiting rate is roughly inversely proportional to pressure. They maintained a constant drift field, while I maintained a drift field proportional to the pressure, so the dependence of rate on pressure should not necessarily be the same for our data as for theirs. Their charge per event was quoted as 26 fC, approximately 60% of our charge per event at 1–3 atm.

Our limiting rates were an order of magnitude greater than theirs. This is primarily due to our use of a narrow slit. The charge diffusion in our detector was 100–200 μm and the electron ranges even greater, so even though a 120 μm slit was used the charge was spread over several hundred μm . The fact that the limiting rate is not inversely proportional to pressure could also be partially due to the slit: the electron ranges are inversely proportional to the pressure so the charge is spread over a smaller area at a higher pressure.

The ratios of the drift current to the cathode current were 0.16, 0.22, 0.35 and 0.62 within an uncertainty of ± 0.02 at 1–4 atm respectively. Babichev *et al* [1] did not increase the drift field with the pressure, hence their drift/cathode current ratio would have remained roughly constant. It is expected that because ions can be collected more rapidly by the cathodes than by drift plane (due to the higher electric field and the shorter drift path), a higher drift/cathode current ratio would increase the space-charge. This, along with the slit, could explain why our gain dropped more rapidly with pressure than that of Babichev *et al*. Experimental validation of the effect of the drift/cathode current ratio on the gain vs. rate curves has not yet been done.

6.3.2 Gain via Multi-Channel Analyzer

Figure 6.13 displays the gain vs. rate results obtained by measuring the position of the 9.70 keV tungsten L_{α} peak with a multi-channel analyzer (MCA).

The first two curves were obtained by placing a 500 μm diameter pinhole in front of the 120 μm slit and using a 70 ns charge integration time. This was an attempt to simulate a more optimized readout system than ours, where coincidence

Figure 6.12: Relative gain vs. rate, measured from detector current.

Figure 6.13: Relative gain vs. rate, measured from MCA peak position.

is only checked between neighbouring anodes rather than over the entire detector. The limiting rate measured under these conditions was under half of the limiting rate due to space charge effects alone.

One of the major contributors to the shift in the peak position is pulse pile up, which occurs for 10% of events at roughly 2×10^7 photons $\text{s}^{-1}\text{mm}^{-2}$ (10^6 counts s^{-1}). Another possible source of peak shift is the lengthening of the signal pulse because of the decreased electric fields in the detector due to the space charge. This would result in a smaller fraction of the total signal charge being collected over the 70 ns integration gate. To verify this effect, the pulse shape would have to be measured at high rates and compared to the pulse shape at low rates.

The remaining curves were obtained with all 16 channels being irradiated through the 120 μm slit, using 100 ns charge integration time. Pulse pile up within the 100 ns gate will occur for 10% of events at a fluence rate of 2.5×10^6 photons $\text{s}^{-1}\text{mm}^{-2}$.

Comparing the data obtained with the slit to that obtained with the pinhole, it is apparent that our system is far from optimized. Decreasing the integration time and making the electronics parallel, such that anode coincidence is not checked over all 16 anodes for each event, would significantly increase the limiting counting rate of the electronics.

6.3.3 Data at 4 Atm

The data obtained at 4 atm are in poor agreement with the other data and are presented separately, in Figure 6.14. The reason that the data do not extend to very high fluence rates is that the GMD suffered electrical breakdown at the last measured point, and I feared that a repetition of the experiment would damage the GMD.

The data from the detector current display a much higher limiting rate than was obtained at 3 atm. However, the spread of all but a few of the points is very broad. In particular the second to last point, for which the error bar primarily indicates systematic rather than random error, is in poor agreement with its neighbours. The MCA data also give a higher limiting rate than the 3 atm data ($1.3 \times 10^6 \text{ mm}^{-2}\text{s}^{-1}$ vs. $9 \times 10^5 \text{ mm}^{-2}\text{s}^{-1}$), in fact they match reasonably closely to

Figure 6.14: Relative gain vs. rate at 4 atm.

the 2 atm data ($1.4 \times 10^6 \text{ mm}^{-2}\text{s}^{-1}$).

The gain used at 4 atm was lower than the gain used at the other pressures, but this is not by itself enough to explain the increased rate ability. There were only 33 fC produced per event compared to 43 fC at 3 atm, which is expected to increase the rate by a factor of only $(43 \text{ fC})/(33 \text{ fC}) = 1.30$. Another possible explanation for the increase is that the methane:xenon ratio was less than 1:9, as is suspected from the gain curves in Section 6.2. This would lead to changes in the transport properties of the gas, which could result in a decrease of the space charge effects.

6.3.4 Limiting Exposure Rate

The photon fluence rate ϕ can be re-expressed as an exposure rate X/t using the following equation, which uses the specific energy to Roentgen conversion factor of $5.451 \times 10^{16} \text{ eV kV}^{-1} \text{ R}^{-1}$ given in Appendix A of Johns and Cunningham [25].

$$\frac{X/t}{\phi} = \frac{E(\mu_{\text{ab}}/\rho)_{\text{air}}}{5.451 \times 10^{16} \text{ eV kg}^{-1} \text{ R}^{-1}}. \quad (6.1)$$

Table 6.4: Predicted Space-Charge Limited Exposure Rates [mR s^{-1}] at 18 keV.

1 atm	2 atm	3 atm
>380	100	25

Determining the exposure rate for the unfiltered 30 kV_p spectrum used for the rate tests is not very informative, because the peak in that spectrum was at 9.7 keV. This is far lower than the x-ray energies used in diagnostic radiology. A more informative energy would be 18 keV, the peak energy of the Mo x-ray tube spectra used for mammography.

Using $(\mu_{\text{ab}}/\rho)_{\text{air}} = 0.714 \text{ cm}^2\text{g}^{-1}$ (interpolated from Table A-3a of Johns and Cunningham [25]), the fluence rate to exposure rate conversion factor is $2.36 \times 10^{-5} \text{ mR mm}^2$ at 18 keV. The space-charge limited counting rates must be divided by $18 \text{ keV}/9.7 \text{ keV} = 1.9$ before the above factor is applied to approximately account for the difference in the charge deposited in the detector per photon. The results of the calculation are given in Table 6.4.

The usual exposure rate for a mammography screen/film cassette can be determined using the mR/s per tube mA data given with spectra on pp. 53 and 125 of Birch and Marshall [56]. The two spectra are respectively 1) a 30 kV_p Mo spectrum with 0.03 mm Mo filtration, and 2) the same but with 5 cm tissue additional filtration. Assuming 100 mA and a source-detector distance of 60 cm, the skin exposure rate (raw beam) is 2300 mR s^{-1} and the screen/film exposure rate (after filtration through the breast tissue) is 14 mR s^{-1} .

The GMD should be capable of counting the tissue-filtered beam at all pressures tested, though a bolus would have to be placed around the edges of the breast to block the raw beam.

6.4 Energy Spectra and Energy Resolution

The energy spectra presented in this section were obtained with an ORTEC 142PC preamplifier unless it is specifically noted that they were obtained through the imaging readout electronics. The abscissa of the spectra is given in terms of the energy

absorbed by the the detector per photon interaction.

6.4.1 Calibration Sources

Two radioactive sources were used to calibrate the energy scale of the MCA during the preliminary stages of my research, but were no longer available at the time that the bulk of the experiments were done. In the absence of the sources, the x-ray tube itself was used to calibrate the MCA.

6.4.1.1 Iron-55

For experiments with argon, ^{55}Fe was used as the calibration source. The absorbed energy spectrum from the GMD (Figure 6.15) consists of the full energy γ peak at 5.90 keV and the escape peak at 2.92 keV which results when the interaction of the γ is followed by the escape of a 2.98 keV argon K fluorescence photon. In other argon spectra, a small peak at 2.98 keV could be seen due to fluorescence photons which were produced in the layer of dead argon in front of the detector and were subsequently absorbed in the GMD. In this spectrum, that peak is hidden underneath the escape peak.

6.4.1.2 Americium-241

Because it produces several well-separated lines over the range of 14–60 keV, ^{241}Am is an ideal isotope for calibrating a detector to be used with a 50 kV_p spectrum. Figure 6.16 gives the energies of the major peaks in the absorbed energy spectrum obtained with a GMD filled to 1 atm with xenon. Two γ emissions at 26.3 keV and 33.2 keV are hidden under the K_{α} and K_{β} escape peaks, which appear 33.8 and 29.7 keV below their 59.6 keV parent peak. The 59.6 keV peak itself is smeared towards lower energies because many of the high-energy photoelectrons and Auger electrons escape from the detector before depositing their full energy.

All of the unlabelled peaks are xenon L fluorescence escape peaks, which appear 4.3 keV below their parent peak.

Figure 6.15: Iron-55 spectrum obtained with argon at 1 atm.

Figure 6.16: Americium spectrum obtained with xenon at 1 atm. The theoretical probability of K fluorescence is 0.743 per event.

Figure 6.17: Unfiltered 30 kV_p tungsten spectrum at 1 atm.

6.4.1.3 Tungsten L Lines

The x-ray tube itself can be used as a calibration source if the filtration is removed. As is shown in Figure 6.17, the L_{α} and L_{β} emission lines are easily seen and reasonably well separated from each other, though not sufficiently so that fitting both of them provides an accurate zero-channel calibration for a multi-channel analyzer. The energies given for each peak are the averages of the emission lines which make up that peak (calculated from the energies of individual lines given on p. 63 of Johns and Cunningham [25]). Depending on the quantum efficiency vs. energy characteristic of the detector (which is pressure dependent), the peaks in the absorbed energy spectrum could shift by as much as ~ 0.1 keV.

The spectrum in Figure 6.17 was obtained using the LeCroy 3001 qVt attached to the readout electronics, using a 150 ns integration gate rather than the usual 100 ns gate. As the detector pressure increased, the bremsstrahlung spectrum became more prominent and it became increasingly difficult to accurately measure the positions of the emission lines.

Table 6.5: Energy Resolution (FWHM) of the GMD for Argon and Xenon at 1 atm.

	Ar: <i>i</i> -C ₄ H ₁₀	Xe:CH ₄	
	5.9 keV	17.7 keV	59.6 keV
$\Delta E_{ab}/E_{ab} \times 100\%$	18%	10.9%	5.2%

6.4.2 Energy Resolution

The energy resolutions for Ar:*i*-C₄H₁₀ and for Xe:CH₄ given in Table 6.5 were measured from Figures 6.15 and 6.16 respectively. The resolution measured for Ar:*i*-C₄H₁₀ agrees with the result of Angelini *et al* [73] for Ar:CO₂.

Veloso *et al* [74] measured the energy resolution of their pure xenon GMD to be 17% at 5.9 keV and 7% at 59.6 keV, and I measured 14% at 17.7 keV from their published ²⁴¹Am spectrum. Their resolution may be worse than ours because they did not mix a quencher with the xenon, and they might have been operating at a very low gain (their goal was the development of a gas-proportional scintillation counter operating with pure xenon, and the GMD operation was exploratory research).

The theoretical xenon energy resolution at 17.7 keV can be calculated using Equation 2.11, using the Fano factor of 0.20 determined by the simulations done by T.H.V.T. Dias *et al* [75]. This gives a theoretical resolution of 3.7% at 17.7 keV, three times as good as our GMD achieved. A value of the Fano factor at 59.6 keV was not found in the literature.

6.4.3 Spectra Used for Spatial Resolution Measurements

Figures 6.18–6.21 provide examples of the absorbed energy spectra for the x-ray beams used for imaging and MTF measurements. The radioisotopes were not available at the time that these spectra were obtained. The 50 kV_p spectrum in Figure 6.18 was matched to a previously obtained 50 kV_p spectrum which had been calibrated, and it was then used to calibrate the other spectra in the figure. For all figures except Figure 6.18, the counts in each spectra were scaled to make it easier to compare them.

Figure 6.18: Spectra used for spatial resolution measurements with 1 atm xenon.

6.4.3.1 10–50 kV_p Spectra for 1 atm Xenon

The spectra obtained at 1 atm are shown in Figure 6.18. The 10 kV_p spectrum was obtained by irradiating all sixteen anodes through a 1 mm horizontal slit, while for the other spectra a 1.5 mm vertical slit was also used. With this second slit in place, low energy electrons will deposit their full energy within the sensitive volume of the GMD but electrons with an energy above ~15 keV can escape. As a result, spectra above 20 kV_p are distorted (the distortion takes the form of high-energy features of the spectrum being smeared towards lower energies).

6.4.3.2 10 kV_p

At 10 kV_p, an increase in pressure is seen to result in a hardening of the spectrum and a reduction of the L fluorescence escape peak at 4.5 keV (see Figure 6.19). The 2 atm spectrum has more counts than the rest between 10–12 keV, possibly because the count rate was too high and there was pulse pile up at the MCA input.

The 3 atm spectrum in Figure 6.19 was not actually used for imaging because the

Figure 6.19: 10 and 13 kV_p spectra obtained with xenon at 1–4 atm.

detected count rate was too low. Instead, a 13 kV_p spectrum was used because it contained the tungsten L emission lines and was therefore much more intense for the same tube current than the 10 kV_p spectrum.

6.4.3.3 30 kV_p

At 30 kV_p, the spectrum is again seen to harden with pressure (Figure 6.20). Some of this is due to the increased attenuation of low energies by the 3.5 mm of dead xenon in front of the detector, and the rest is due to the increased quantum efficiency of the detector at high energies. The effect is most pronounced going from 3 to 4 atm.

The incident spectrum shown in Figure 6.20 was taken from Birch and Marshall [56], with the correct amount of Al filtration being simulated using the x-ray attenuation coefficients given in UCRL-50400 [57]. The differences between this spectrum and the absorbed energy spectra are quite pronounced. The escape of the 4.3 keV L fluorescence photons and of high-energy electrons smears the spectrum towards lower

Figure 6.20: 30 kV_p spectra obtained with xenon at 2-4 atm.

Figure 6.21: 50 kV_p spectra obtained with xenon at 2-4 atm.

energies. The fact that fewer fluorescence photons escape at higher pressures could account for some of the apparent hardening in the 4 atm spectrum.

The two small peaks at 5 and 6 keV are an interesting feature. These are the escape peaks from the tungsten L_{α} and L_{β} lines at 8.4 and 9.7 keV (the lines themselves can barely be seen as bumps on the bremsstrahlung spectrum). These lines do not appear on the plot of the incident spectrum because they are strongly filtered by the aluminum, however, the quantum efficiency of our GMD is so much higher at low energies than at high energies that they appear in the GMD spectrum. At high pressures these peaks are subdued.

6.4.3.4 50 kV_p

The structure of the 50 kV_p spectra from the GMD shown in Figure 6.21 is quite interesting. The efficiency of the GMD climbs by a factor just less than 5 (the K-edge jump ratio) at 35 keV, but 89% of K shell absorptions are followed by the escape of a K fluorescence photon. As a result, the K edge is shifted down by 30 keV to 5 keV and the the GMD spectrum looks nothing like the incident spectrum.

If there were no dead xenon in front of our GMD, then one would expect to see a small remnant of the K edge at 35 keV. However, the dead xenon acts as a K-edge filter and suppresses the spectrum past 35 keV, the effect being most severe at 4 atm. The resulting inverted edge is smeared towards lower energies by the escape of 4.3 keV L fluorescence photons and of high-energy electrons. This smearing is less pronounced at 4 atm.

The small peak at 14 keV is a mystery. It could be the result of K Auger electrons, which have energies from 24–33 keV and can produce escape peaks similar to fluorescence photons, but smeared towards higher energies because the electrons lose some of their energy to the detector before escaping. The escape of the KLL Auger would result in the K edge being reproduced at 11 keV plus the portion of the energy deposited by the electron before its escape: it is hard to imagine that the result would be a sharp peak at 14 keV.

6.5 Images

All of the images presented in this section were obtained using a GMD filled with Xe:CH₄. The images shown in Figure 6.22 have been magnified 10 $\times$, in addition to the 1.062 $\times$ magnification factor of the imaging system itself. The scale provided on the figure indicates distances in the plane of the GMD (dividing by the system magnification factor will give distances in the object plane).

The four numbers to the right of each image indicate 1) the highest and lowest pixel values present in the image data, and 2) the pixel values which have been matched to the highest and lowest available grey levels (see Section 6.1.2.1 for a more complete discussion of these numbers).

6.5.1 Early Images: Circuit Components

The data sets for the first three images (Figure 6.22 (a), (b), and (c)) were obtained using a 50 kV_p beam with the GMD operating at 1 atm. These images were generated before the modifications to the image generation software had been implemented: no channel gain calibration was applied, and the threshold centroid calculation was used instead of the 3.4.5-channel weighted centroid calculation.

In Figure 6.22(b), the mismatched channel gains have resulted in an artifact near to the left edge of the image: three parallel vertical lines running the length of the image which correspond to three of the GMD anodes. In Figure 6.22(c) the second to last column of pixels is missing completely because the pixel efficiency for that column was extremely low, and the image generation software was set to not apply pixel efficiency correction factors larger than 10.

These three images were obtained when our GMD research group first became interested in developing GMD technology for x-ray inspection of micro-electric circuits, and are meant to demonstrate the abilities of the GMD for this application. X-ray inspection is used in the micro-electronics industry to look for faults in circuits, both as a diagnostic for circuits requiring repairs and as a screening method for new circuits.

Figure 6.22: Several images obtained with Xe:CH₄ in the GMD, magnified 10 $\times$.

6.5.1.1 Images of an Integrated Circuit

Figure 6.22(a) and (b) show a small section of a 14 pin integrated circuit. The images were generated from the same data set, the difference being that image (b) was generated using only those events for which less than 15 keV was deposited in the detector. The reason for doing this will be discussed below.

The silicon chip itself is mounted on an electrostatic shielding plate which forms the dark oval in the centre of the image. The dark lines radiating from the centre are connected to the pins of the IC: the fine wires leading from these lines to the chip itself were too small for the GMD to resolve.

Compared to images (not shown) presented in a brochure for a commercial x-ray inspection system, the CS-100 from Micro Focus Imaging Corporation (225 Larkin Dr., Wheeling, IL 60090), images (a) and (b) are poor in terms of spatial resolution. The commercial system (which uses a 4" image intensifier coupled to a CCD camera) applies a $\geq 3\times$ magnification factor in conjunction with a microfocus x-ray tube to obtain 20–40 lp mm⁻¹. Now that our system is operating at 4 atm, it provides a resolution of >8.8 lp mm⁻¹ (in the object plane) for 50 kV_p x rays at $1.062\times$ magnification.

These images were also used to demonstrate the use of energy discrimination to enhance images obtained with the GMD. Image (a) is smeared out horizontally, as a result of high energy, long range electrons produced in the gas (L photoelectrons and K Auger electrons). This smearing is not seen in the vertical direction because the horizontal lines of the image are obtained in sequence (as part of the SPR scan) rather than simultaneously. Hence, there cannot be charge spread between them.

As was discussed for the 50 kV_p absorbed energy spectrum in Figure 6.18, absorbed energies between 5 and 15 keV correspond primarily to the interactions of 35–45 keV x rays which are followed by the escape of 30 keV K fluorescence photons. For image (b), an energy discrimination threshold was placed at approximately 15 keV. Events above the threshold were rejected, including those events for which 1) the x rays interacted with the L shell, producing a high-energy L fluorescence photon and 2) the x rays interacted with the K shell but a high-energy Auger electron was

Figure 6.23: Image of a ball grid array, with profiles taken through the solder balls.

produced rather than a fluorescence photon. As a result of the energy selection, the streaking is almost completely eliminated.

6.5.1.2 Image of a Ball Grid Array

Figure 6.22 (c) was obtained to demonstrate the possible use of a GMD imaging system to check IC mounting. It shows four solder balls in a TopLine™ ball grid array, which is a surface mounting method in which the integrated circuit is mounted to the circuit board via a rectangular array of 0.5 mm diameter solder balls.

Figure 6.23 is a mock-up demonstration of how the image could be used to inspect the ball grid array. The profiles, which are labelled according to the line through the image which they correspond to, give a clear indication of the relative thickness of the solder balls and can therefore be used to determine whether each ball is bonded to both the IC and the board. For this particular task, the GMD has sufficient resolution even at 1 atm.

Figure 6.24: Image of a very fine copper braid obtained at 13 kV_p.

6.5.2 Later Images

The final two images in Figure 6.22 were produced using the final version of the image generation software, which implemented the image generation method described in Chapter 4.

6.5.2.1 Copper Braid Image

The purpose of Figure 6.22(d) is simply to demonstrate the very high resolution that the GMD can provide for low energy (13 kV_p) x-ray beams. The image is reproduced at higher (20×) magnification in Figure 6.24 so that the $25 \times 50 \mu\text{m}^2$ (width $\times$ height) pixels can be seen. The fan-beam slit projects a $92 \mu\text{m}$ (FWHM) thick line onto the GMD, while the FWHM for the LSF perpendicular to the fan beam was $80 \mu\text{m}$. Hence, apart from the effect of the pixel size, the resolution is approximately equal in the horizontal and vertical directions.

The object was a small piece of copper braid made of wires approximately $60 \mu\text{m}$ in diameter. The tick marks on the scale are placed at the anode locations, to indicate that the details visible in the image are significantly smaller than the detector pitch.

Table 6.6: Rejection of events and image generation efficiency.

Multi-Peak	Single-Anode	Diffuse	η_{gen}
6.5%	3.4%	0.02%	90.0%

6.5.2.2 Shell Images

The snail shell image of 6.22(e) was obtained at 4 atm using a 25 kV_p spectrum filtered with 0.5 mm Al and 22.0 mm lucite. The snail shell was chosen because 1) it is small enough (9 mm × 6 mm) to be imaged by our GMD in only a few passes. 2) the high mineral content of the shell compared to soft biological samples provides enough x-ray attenuation to provide reasonable contrast, and 3) the structure of the shell is fairly detailed.

The image was acquired over four separate data runs, each providing a 2.5 mm panel, because the 2.6 mm wide field of view of the detector was too small to capture the entire image at once. Because the live time correction (described in Section 4.3) was applied to each panel individually, the panels did not match each other when they were first generated. The pixel values with a portion of the white area in each panel were averaged to provide a reference intensity for each panel, and the intensities of the second, third and fourth panels were rescaled to match that of the first panel.

In addition, there was some drift in the system over the 34 hour acquisition time which had to be corrected for. A few lines of the background in each panel were averaged together and applied to the entire panel in precisely the same manner as the usual pixel efficiency calibration (see Section 4.2.2).

The number of events rejected by the image generation software was recorded for this image, to determine whether the DQE of the imaging system was being seriously compromised by the many rejection criteria (see Section 4.5). Table 6.6 indicates the percentage of events rejected due to several of the criteria. The image generation efficiency of 90% is good, but could be improved by tweaking the rejection criteria. Rejection of multiple-peak events results in the greatest cost. These events are thought to primarily result from L fluorescence photons interacting some distance away from the primary interaction location, and some additional criteria could be

added to try to distinguish the main peak from the fluorescence peak.

Figure 6.25 shows a variety of different analyses applied to the image data. Figure 6.25(a) shows the image at actual size, while the other panels provide $5\times$ magnification. The next image, (b), is a coarse, low-statistics image of the shell generated prior to the acquisition of the final image data to ensure that the alignment was correct. Image (c) is the same image shown in Figure 6.22(e).

Images (d) and (e) show alternatives to the usual centroid reconstruction method. The first shows the result of applying a discrimination threshold to each anode channel (done in the software, rather than using the discriminator electronics) and then doing reconstruction via the binary centroid equation (Equation 2.22). The resulting image has $100\text{ }\mu\text{m}$ wide pixels, half the anode pitch. This and the poorer accuracy of the binary centroid lead to a resolution less than that of (a). In situations where very high resolution is not needed however, this method of image generation represents an alternative method of image generation which is easier to implement than our method.

Image (e) was obtained by integrating the ADC counts on each anode rather than calculating the centroid of each event. The resulting image is similar to what one would obtain by imaging with a strip ionization chamber, where the pixel width is equal to the strip pitch. The $\sim 150\text{ }\mu\text{m}$ diffusion width of the primary electron cloud becomes the limiting factor in the resolution of the system, whereas it does not significantly affect the resolution of our system. As can be seen, there is an enormous benefit to using a GMD in counting mode rather than simply integrating the collected charge.

Images (f) through (h) demonstrate the energy discrimination ability of the GMD. A software discrimination threshold was placed at 18 keV and the data separated into two images. The low-energy image has superior contrast, though the difference between the average energies of each image would have only been $\sim 5\text{ keV}$. Image (h) is the ratio of the low over the high energy image. The image is faint, but it demonstrates that the difference between images (f) and (g) is not simply a scaling factor.

Figure 6.26 clearly demonstrates another difference that can be seen between the

Figure 6.25: Images of a small snail shell.

Figure 6.26: Resolution enhancement/degradation by energy selection.

low and high energy images. The maximum resolution indicated by the $MTF(f) = 0.05$ points is 7.5 lp mm^{-1} for the low energy image and 5.0 lp mm^{-1} for the high energy image.

Chapter 7

Discussion and Conclusions

This chapter summarizes the results presented in Chapter 6 and the insights which have been gained into the operation of the GMD. Some general conclusions are drawn and recommendations for future work are provided.

7.1 Summary and Discussion of Results

The properties of the GMD which are most pertinent to imaging are the spatial resolution, the space-charge limited counting rate, the DQE, and the overall image quality.

7.1.1 Spatial Resolution

The spatial resolution of the GMD is very promising. For 4 atm xenon, the highest pressure at which measurements were made, the resolution is $>6.5 \text{ lp mm}^{-1}$ for 30 kV_p x rays and $>8.2 \text{ lp mm}^{-1}$ for 50 kV_p x rays. However, the 50 kV_p MTF falls off very rapidly at low spatial frequencies: it crosses 0.5 at 1.6 lp mm^{-1} , compared to 2 lp mm^{-1} for the 30 kV_p MTF.

The highest resolution observed was 11 lp mm^{-1} for a 13 kV_p incident spectrum, this being in an image of the finest-pitch test pattern we had available. The MTF, however, indicates that $13\text{--}14 \text{ lp mm}^{-1}$ could have been resolved. By further increas-

ing the pressure of the detector similar resolution should be attained at higher kV_p : for example, the resolution at 30 kV_p increased by a factor of 1.6 between 2 and 4 atm, so approximately 10 lp mm^{-1} is expected at 7–8 atm.

The determining factors for the resolution are reasonably well understood. The RMS spatial resolution of the GMD agrees with the model presented in Chapter 2 for incident x-ray spectra below 40 kV_p , and the disagreement at 40 kV_p and 50 kV_p appears to be due to the rejection of events which produce spatial charge distributions more than five channels (1 mm) wide. However, the model was only able to predict that the resolution should fall within a fairly broad range, because the known geometry of the drift volume was not used to refine the model.

It was expected that the resolution would scale with the pressure, and this is approximately true for a subset of the data (the 10 kV_p data from 1–3 atm and the 30 kV_p data from 2–4 atm). The reason that this is not the case for the remainder of the data is thought to be that 1) the absorption spectrum changes as a function of pressure, and 2) the fraction of fluorescence photons which escape decreases with increasing pressure.

It has not yet been determined if the best MTF observed represents the limit of the system. It was originally thought that the 13 kV_p MTF did not significantly change between 3 and 4 atm because the limit had been achieved; however, the predicted RMS error due to noise was only 12 μm compared to the 46 μm RMS width of the line-spread functions at 4 atm. This suggests either that a very significant source of error has not been taken into consideration, or that the resolution did not improve between 3 and 4 atm because fewer fluorescence photons escaped from the detector at 4 atm.

The contributions of each of the various sources of resolution loss could be measured independently. To give a few examples, the gain could be decreased to increase the effect of electronic noise, the diffusion could be increased by changing the drift field, and the fraction of fluorescence photons which escape can be increased by changing the geometry of the drift volume.

7.1.2 Limiting Counting Rate

The space-charge limited counting rate of the detector was found to be $>2 \times 10^6$ photons $\text{mm}^{-2} \text{s}^{-1}$ at 3 atm. compared to $>3 \times 10^7$ photons $\text{mm}^{-2} \text{s}^{-1}$ at 1 atm. Converting these to exposure rates at 18 keV provides $>25 \text{ mR s}^{-1}$ and $>380 \text{ mR s}^{-1}$ respectively. compared to the estimated detector exposure rate of 14 mR s^{-1} behind the patient for a Mo-anode mammography unit operating at 30 kV_p and 100 mA. The raw-beam exposure rate (without the breast shielding the detector) is estimated to be 2300 mR s^{-1} . indicating that if the GMD were used under these conditions a bolus might have to be used around the edges of the breast.

The 4 atm counting rate data are incomplete. However, for the data which were collected, the gain vs. rate curve matches roughly with the 2 atm data rather than showing a more rapid drop off than the 3 atm data as expected. The detector was operated at a lower gain at 4 atm (350 vs. ~ 500), but this is not expected to increase the space-charge limited counting rate by as much as was seen (a factor of >4). It is suspected that the improved rate ability is instead due to an increased Xe:CH₄ ratio, though it is not known by how much this should affect the rate ability.

The results, though very promising with regard to the use of the GMD for medical imaging, demonstrate a lack of understanding of how the operating parameters of the GMD affect the rate ability. Three parameters mentioned above are the pressure, the gas gain, and the gas composition. These and other parameters such as the drift field and the width of the slit through which the GMD is irradiated should be examined at some point in the future.

7.1.3 Detective Quantum Efficiency

Ideally, the DQE of a photon-counting detector would be equal to the quantum efficiency. Our system, however, applies a set of event rejection criteria which are meant to improve the MTF of the system. As a result, only $\sim 80\text{--}95\%$ of the detected photons are included in the image. A thorough investigation of the rejection criteria should be performed at some point in the future, in order to determine 1) whether the improvement in image quality for each criterion outweighs the reduction in DQE.

and 2) what the optimum rejection thresholds are.

The quantum efficiency of our detector is itself fairly low, because the x-ray path length through the drift volume is only 3.9 mm. At 4 atm the QE is estimated to be 15-20% at 30-50 kV_p from Figure 2.2, and doubling the pressure would increase it to only ~30%. To achieve high QE, therefore, the x-ray path length through the xenon must be increased.

7.1.4 Image Quality

Other than the measurement of the MTF for our system, the image quality has not been quantitatively assessed. There were systematic artifacts in earlier images, before the anode channel gains had been calibrated, but these are not present in later images. Subjectively, the image quality is very good considering that GMD imaging is still in its infancy.

A pixel efficiency correction must be applied to the image in order to achieve image uniformity, however, and this is of some concern. The correction scales the pixel values in each column of the image either up or down by $\pm 20\%$, the result being that the pixel values are only approximately equal to the actual number of photons binned into the pixels. The effect this has on the DQE should be examined unless the necessary correction factors can be substantially reduced, using the methods which will be proposed in Section 7.4.3.

7.1.5 Energy Resolution

The energy resolution at 17.7 keV was 10.9% (1.9 keV) and at 59.6 keV was 5.2% (3.1 keV). This suggests excellent potential for energy discrimination. However, the above resolutions are only truly indicative for the energy discrimination between monoenergetic lines, where the fluorescence escape peaks can be easily distinguished from the primary peaks. In the case of polyenergetic spectra with a maximum energy below the xenon K edge, discrimination can be as poor as >4.3 keV if L fluorescence escape is as common as L fluorescence capture, and as poor as >30 keV for continuous spectra which extend across the 34.5 keV K-edge.

7.2 Deterioration of the GMD with Age

Both of the GMD prints used for the work presented here were found to deteriorate rapidly, the deterioration taking the form of spontaneous discharges which became very frequent (>1 per minute) after only one month of operation. The previous print (used by myself and by my predecessors) had been mounted for 10 months before showing similar problems, having been operated on a regular basis for 2.5 of those months (non-consecutively).

If the GMD is to be marketed as an imaging device, then it must operate reliably for years rather than months. The rapid deterioration of our prints is a major concern, and methods of increasing their useful lifetime must be considered.

The rapid deterioration of the prints is thought to be the result of defects in manufacture. For example, if there is small promontory on the edge of one of the cathode strips, then the local electric field at that position will be stronger than in adjacent regions of the cathode and ions will be preferentially collected at that point. As a result, the rate of damage at that point will be accelerated. If a promontory large or sharp enough is formed, then the local electric fields become strong enough to tear electrons from the cathode and produce a spontaneous avalanche in the detector. Damage on the edges of certain cathodes on two prints previously used in the detector was observed to be fairly severe.

This problem could be aggravated by the presence of contaminants in the gas, which would be ionized in the avalanche and bombard the cathodes. Regarding this possibility, the use of Humiseal to passivate the ends of the strips may accelerate the deterioration of the print, as Humiseal cures by releasing hydrocarbon solvents. The use of a high-grade epoxy such as E-505 (Epotecny, 10 Impasse Latécoère, F-78140 Vélizy France) should be tried in the future, to see if this results in a longer print lifetime.

Another form of deterioration, referred to as ageing, is the gradual loss of gain in the GMD with time. Though no evidence of ageing has been seen for our detectors, it defines the ultimate lifetime of a well-manufactured GMD and has been investigated in some detail by Bouclier *et al* [76] [77] regarding the use of the GMD in high-energy

physics experiments. The primary mechanisms of ageing are the polymerization of the quencher onto the strips and the deposition of contaminants in the fill gas onto the strips [76].

Bouclier *et al* [76] have demonstrated that, under the right conditions (constant gas flow, controlled gas purity, and dimethyl ether used as the quencher), a GMD can collect >120 mC of avalanche charge per strip-centimetre without its performance being reduced. For a $200\text{ }\mu\text{m}$ detector, this equates to $>60\text{ mC mm}^{-2}$ or, assuming an average absorbed energy of 22 keV per photon and a gas gain of 500, an absorbed fluence of $>1.1 \times 10^{12}$ photons mm^{-2} .

Continuing this calculation further, the data on p. 125 of Birch and Marshall [56] give a fluence rate of 8×10^3 photons $\text{mm}^{-2}\text{s}^{-1}\text{mA}^{-1}$ for a 30 kV Mo spectrum, using a 60 cm source-detector distance and 5 cm of tissue in front of the detector. This suggests that the lifetime of a properly constructed and cared for GMD in a mammography unit could be $>1.4 \times 10^8$ mA s.

7.3 Conclusions

The results indicate that the GMD could operate under the fluence rates required for clinical digital radiography up to at least 4 atm, and can provide sufficient spatial resolution for many imaging tasks. Increasing the pressure to 7 atm should improve the resolution to approximately 10 lp mm^{-1} at 30 kV_p , though there would be a decrease in the space-charge limited counting rate.

The quantum efficiency and therefore the DQE of our detector is low, but we intend to increase both the pressure (by a factor of approximately two) and the xenon depth (by a factor of at least two) in order to increase the QE. A depth $\times$ pressure product of 35 mm atm would provide a QE greater than 0.90 below 50 kV_p , and greater than 0.50 below 150 kV_p .

The most serious concern with our detectors is their reliability. This is thought to be due to faulty manufacture or contamination of the gas.

7.4 Future Work

Several suggestions have been made in Section 7.1 regarding GMD phenomena which could be investigated in the future. In addition to basic research to increase our understanding of the GMD, effort should be continually applied to improve the imaging system with the goal of eventually developing a practical device for medical or industrial x-ray imaging.

7.4.1 Recommended Modifications to the System

The following improvements, in order of precedence, should be made to the system before substantial additional work is done.

First, the $24\text{ M}\Omega$ cathode protection resistance should be substantially reduced, as noted in Section 3.2.2.3. The voltage drop across this resistance due to the dark current of the detector is very large, as high as 40 V, and fluctuations in the dark current (which cause changes in the voltage drop) are thought to be the source of some gain variations that have been seen.

Second, the data acquisition software should be modified so that it spends the same amount of live time on each line of the image. Currently the time is set by the real time clock in the data acquisition computer. The number of counts in the live time scaler in the electronics could be converted to seconds by comparing the number of counts in the real time scaler to the computer clock.

Finally, the thickness of dead xenon in front of the detector should be reduced. Currently the drift plane is mounted such that it cannot be brought any closer to the detector window. Either a new drift plane could be constructed, or the inside of the detector window could be metallized.

7.4.2 Increase of Detector Pressure

The pressure vessel has a design pressure of 7 atm absolute. Once the current GMD print has been replaced, spatial resolution and counting rate measurements could be continued up to this pressure. I suggest, however, that only the detector

current method be used to measure the limiting counting rate because it is faster than using the multi-channel analyzer method. An additional benefit is that the GMD would therefore be exposed to high fluence rates for a shorter period of time per measurement and would therefore last longer.

An attempt could be made, by increasing the drift voltage proportional to the increase in the cathode voltage as the pressure is raised, to maintain a constant drift current to cathode current ratio. Hopefully this would allow the space-charge limited counting rate to be measured as a function of pressure alone.

7.4.3 Keystone Geometry

A keystone detector is one in which the detection elements follow rays emanating from a focal point (see Figures 7.1 and 7.2). The keystone geometry permits the path length of the x rays through the detector to be very long, because the x-ray paths follow the strips and there is therefore no blurring due to parallax error. Keystoned multi-wire proportional chambers have been used successfully by Baru *et al* [34] for many years, and Kiourkos *et al* [78] have done preliminary research on keystoned gas microstrip detectors.

The keystone geometry has several advantages over the perpendicular geometry we now use. The primary advantage, which was already mentioned, is that the depth of the detector can be increased without introducing parallax error. By using 5 cm of xenon at 7 atm, the quantum efficiency could be increased to 90–95% at 30–50 kV_p. Additional advantages are the following:

First, the ionization produced by the incident x-rays is distributed over a large area of the print, in contrast to the perpendicular geometry where the ionization is collected over a sub-millimetre width strip across the print. Both the space charge and the rate of ageing due to quencher polymerization are functions of the rate of charge collection per unit area: therefore a keystone print should have a space-charge limited counting rate approximately two orders of magnitude higher, and a polymerization-limited ageing rate approximately two orders of magnitude lower, than prints with our current geometry.

Figure 7.1: Concept diagram of a keystone geometry detector for use in scanned-projection radiography or benchtop CT.

Figure 7.2: Sketch of a keystone print pattern. Not to scale.

Second, the x-ray interactions always occur the same distance from the strips, hence the primary electron drift distance is a constant. This means that diffusion in the detector is also a constant, and may be controlled by changing the drift distance. The systematic error in the centroid calculation is determined by the diffusion, hence either 1) the diffusion can be set to minimize the error, or 2) a bias correction can be applied after the centroid has been calculated to eliminate the systematic error.

If a bias correction were applied with our current imaging system, then it would accurately correct the centroid only for x rays which interact a certain distance from the print. In a keystone system, a simple centroid calculation with a large systematic error (e.g. the 4-channel centroid) could possibly be used with a bias correction, rather than the weighted centroid method currently in use. This would be of considerable advantage if the centroid calculation is to be hard-wired into the readout electronics.

One disadvantage of the keystone geometry is that, because of the long x-ray path length through the detector, it is extremely sensitive to misalignment. For example, if a keystone detector with 5 cm strips is misaligned by only 0.23° , then the rear of the detector will be shifted $200\text{ }\mu\text{m}$ with respect to the front.

Another concern is that the x-ray tube focal spot penumbra will be larger in a keystone detector than in a thin detector such as a screen-film cassette. The reason for this is that the photons interact, on average, one mean free path into the detector, and hence at least one mean-free path from the object. Because the focal spot penumbra is proportional to the object-detector distance, the resolution will be compromised if the mean-free path is too long (i.e. the gas pressure is too low for the x-ray energies being used).

7.4.4 Benchtop Computed Tomography

Because the GMD provides one-dimensional position readout, it is natural to consider using it for computed tomography (CT). It would be impractical to use a $200\text{ }\mu\text{m}$ pitch GMD for clinical head and body CT, a modality which demands a resolution of only $\sim 1\text{ mm}$, but the GMD could be used in high-resolution benchtop CT system for examination of small animals and tissue samples.

Our current imaging system would require very little physical modification for it to be made CT-capable, simply the addition of a computer-controlled rotation stage on which to mount the object. The image generation software would require no modification, rather, an additional layer of software could be written to do CT reconstruction of projections generated by the current software.

7.4.5 Dual Energy Radiography

The applicability of the GMD to dual-energy radiography [79] could be tested by attempting to produce dual-energy images of an object containing regions of material with widely differing mean atomic numbers. The discrimination thresholds would have to be chosen carefully because of the spectral distortion caused by K fluorescence escape. It might be found, because of the widely differing resolution between different x-ray energies, that the low energy image must be blurred in order for the subtraction to be effective.

7.4.6 Improvements to the Data Readout

Currently, the data rate of the GMD system is limited to $<400 \text{ events s}^{-1}$ by the data acquisition computer. A typical calibration run, by comparison, requires $>5 \times 10^5$ events and a small image requires $>10^7$ events. Some of the larger images required several days of continuous data acquisition.

Simply using a faster computer for data acquisition could substantially increase the data rate. A factor of eight increase in the data rate, for example, would mean that large images could be acquired in hours rather than days.

Eventually, if the GMD imaging system is to be marketed as a practical medical imaging device, the image generation will have to be done by dedicated electronics rather than by software. Designing and implementing the electronics will be no mean task, as any dead time in the electronics at high counting rates will result in a loss of DQE.

7.4.7 Ultimate Goals

At some point in the future, our research group will have to decide on a particular imaging application for a GMD-SPR or a GMD-CT system. Industrial or research applications, such as the examination of electronic circuits or of biological specimens, would require only a 2.5–10 cm wide GMD with 128–512 anodes. Depending on the application, the system could provide 1 to 10 pixels per anode pitch. Medical imaging applications, by comparison, would require a 20–35 cm wide GMD with 1024 anodes and a data acquisition system capable of producing an image within a few seconds.

The intermediate-term goal for the next 5–7 years would be to build a 128–512 channel SPR system, preferably with CT capability and a keystone geometry. Such a system would be a valuable quality-control tool in industry or research tool for hospitals and academic institutions.

The gas microstrip detector will not, for at least the next several years of its development, be able to compete with the medical digital radiography technologies currently being commercialized in terms of either cost or reliability. However, just as digital radiography was first developed nearly thirty years ago but is now expected to gradually replace screen-film as the standard for medical radiography, it is expected that photon-counting radiography will surpass the more conventional methods of digital radiography at some point in the future.

Appendix A

Atomic Physics of Xenon

The purpose of this appendix is to present a comprehensive description of the atomic physics of xenon as it relates to the ionization of xenon in the gas microstrip detector. For items which were discussed in Chapter 2, only the data tables and a concise summary will be provided.

A.1 Binding Energies and Vacancy Probabilities

The binding energies E_X for xenon are given in Table A.1. Where average binding energies are given, they are weighted averages over the number of electrons in each subshell. As discussed in Chapter 2, the edges in the xenon absorption spectra occur at the binding energies.

Also as discussed in Chapter 2, the vacancy probability V_X is the relative probability that a photoelectric absorption will occur in shell X. The vacancy probabilities for the K, L, and higher shells in xenon are given in Table A.2.

A.2 Relaxation Cascade

After an electron has been ejected from an atom by the photoelectric effect, the newly-created vacancy is filled by an electron from a higher shell in radiative (fluorescence) or non-radiative (Auger) transition. Transitions which occur between sub-

shells within a single shell are classed, both radiative and non-radiative, as Coster-Kronig transitions.

Throughout this section, the various transition probabilities given were calculated from the theoretical x-ray emission rates of Scofield [80] and the theoretical electron emission rates of Chen, Crasemann and Mark [81]. For the sake of simplicity, I have not adjusted these rates in the cases where there are multiple vacancies in the atom. All transition energies were calculated using the data in Table A.1.

A.2.1 Fluorescence

When a transition produces a fluorescence photon, the energy E_f of the photon is given by

$$E_f = E_X - E_Y \quad (\text{A.1})$$

where E_X and E_Y are the binding energies, respectively, of the initial vacancy and the final vacancy.

The K fluorescence lines for xenon (the fluorescence energies emitted as a result of an electron filling a vacancy in the K shell) are given in Table A.3, along with their relative transition probabilities T_f . The K_{α_1} and K_{α_2} lines are presented for demonstration purposes only. In any calculations their weighted average K_{α} is used.

The fluorescence yield ω_X is the probability that the filling of a vacancy in shell X occurs by a fluorescence transition rather than by an Auger transition. For the K shell, the yield is $\omega_K = 0.889$.

For the L shell the fluorescence yield is determined, along with the average fluorescence energy, from the primary distribution of vacancies N_1 , N_2 , and N_3 among the L_1 , L_2 and L_3 subshells. The values given in Table A.4 were calculated using the average fluorescence energies for each subshell and the theoretical fluorescence yields and Coster-Kronig transition probabilities. Coster-Kronig transitions must be accounted for in the calculations because they can shift vacancies from one L subshell to another before the fluorescence photon is emitted. A good discussion of this is provided in Bambynek *et al* [82], and I have outlined the calculation on Page 144.

Finally, M fluorescence can be disregarded because $\bar{\omega}_M < 0.01$ (Bambynek *et al* Table V.IV [82]) and $\bar{E}_f < 1$ keV.

A.2.2 Auger Transitions

An Auger transition occurs when the filling of a vacancy results in the emission of an electron from the atom. In medical physics Auger electrons are generally thought of as being “soft” because, for oxygen and carbon, their energy is less than 0.5 keV. For xenon, however, they can have energies in excess of 30 keV.

The notation for an Auger transition is XYZ, where X is the shell with the initial vacancy and Y,Z are the shells with the final vacancies (one electron having filled the X vacancy and the other having been ejected). By convention, Y and Z are stated in order of decreasing binding energy.

The energy E_a of the emitted electron is

$$E_a = E_X^Z - (E_Y^Z + E_Z^{Z+1}) \quad (\text{A.2})$$

where E_X^Z and E_Y^Z are the X and Y binding energies for xenon (atomic number $Z = 54$) and E_Z^{Z+1} is the Z binding energy for cesium ($Z = 55$). The next-highest atomic number is used for shell Z to account for the increase in binding energy due to the vacancy in shell Y. Cesium binding energies were taken from Huang *et al* [83].

The K Auger electron energies and relative transition probabilities are given in Table A.5. The total number of K Auger transitions per K vacancy is $a_K = 0.111$.

Following a KLL Auger transition, there are two L shell vacancies which must be considered for subsequent L Auger and fluorescence transitions. I have made an approximation by using the same L Auger and fluorescence yields for both the first and second transition.

Finally, the average L Auger electron energies and yields $\bar{a}_L = 1 - \bar{\omega}_L$ are given in Table A.6. These were calculated using the same method used to calculate the average L fluorescence energies and yields.

Table A.1: Xenon electron binding energies (absorption edges) in keV.

K	L ₁	L ₂	L ₃	M ₁	M _{2,3}	M _{4,5}	N ₁	N _{2,3}	N _{4,5}	O _{1,2,3}
34.582	5.452	5.100	4.781	1.152	0.964	0.681	0.223	0.161	0.067	0.015

K and L from UCRL-50400 [57], others from Huang *et al* [83].

Table A.2: Vacancy probabilities for xenon.

	V_K	V_L	V_{M+N+O}
$E < E_L$	0	0	1
$E_L < E < E_K$	0	0.7874	0.2126
$E > E_K$	0.8354	0.1296	0.0350

From UCRL-50400 [57].

Table A.3: K-fluorescence lines and relative intensities for xenon.

	K_{α_1} (K-L ₃)	K_{α_2} (K-L ₂)	K_{α} (K-L _{2,3})	K_{β} (K-M,N,O)
E_f [keV]	29.801	29.482	29.689	33.768
T_f	0.532	0.287	0.819	0.181

Table A.4: L fluorescence in xenon according to mode of vacancy production.

	K_{α} fluor	KLL Auger	KLX Auger	τ_K photo	τ_L photo
E_f [keV]	4.269	4.322	4.323	4.280	4.307
$\bar{\omega}_L$	0.097	0.095	0.094	0.097	0.096

Table A.5: K Auger electron average energies and relative probabilities.

	KLL	KLX	KXY
E_a [keV]	24.240	28.631	32.741
T_a	0.655	0.316	0.029

Table A.6: L Auger emission in xenon according to mode of vacancy production.

	K_{α} fluor	KLL Auger	KLX Auger	τ_K photo	τ_L photo
E_a [keV]	3.415	3.520	3.513	3.435	3.483
$\bar{a}_L$	0.903	0.905	0.906	0.903	0.904

Table A.7: Xenon L shell Coster-Kronig transition probabilities

f_{12}	f_{13}	f_{23}
0.172	0.292	0.175

Table A.8: Average L-fluorescence energies for xenon by subshell.

	L ₁	L ₂	L ₃
E_f [keV]	4.650	4.488	4.163
ω_L	0.041	0.090	0.092

A.2.3 Coster-Kronig Transitions

A Coster-Kronig transition is a rearrangement of vacancies between the subshells of a single shell, resulting in the release of a soft electron or (though the probability is negligible) a soft photon. These transitions are analogous to those which produce Auger electrons and fluorescence photons, but are classed separately.

The energies involved in xenon Coster-Kronig transitions are below 1 keV, so we are concerned only with their effect on the L fluorescence and Auger emissions. The Coster-Kronig transition probability is denoted by f_{ij} , where the subscripts i and j denote, respectively, the subshell with the initial vacancy and the subshell with the final vacancy.

The transition probabilities given in Table A.7 were used to calculate $\bar{\omega}_L$, $\bar{E}_f$, $\bar{a}_L$, and $\bar{E}_a$ as given in Tables A.4 and A.6 using the following method. First, the primary vacancy distribution N_i is determined. For example, following a K_α transition $N_1 = 0$, $N_2 = T_{K-L_2}/(T_{K-L_2} + T_{K-L_3}) = 0.3507$, and $N_3 = T_{K-L_3}/(T_{K-L_2} + T_{K-L_3}) = 0.6492$ where T is the fluorescence transition probability. The final L subshell vacancy distribution V_i resulting from an initial vacancy distribution N_i is given by (see Bambynek *et al* [82] for a derivation)

$$\begin{aligned}
 V_1 &= N_1, \\
 V_2 &= N_1 f_{12} + N_2, \\
 V_3 &= N_1 (f_{12} f_{23} + f_{13}) + N_2 f_{23} + N_3.
 \end{aligned}
 \tag{A.3}$$

Given the final vacancy distribution, the average fluorescence yield is

$$\bar{\omega}_L = \sum_i V_i \omega_{Li}
 \tag{A.4}$$

and the average fluorescence energy is

$$\bar{E}_L = \frac{\sum_i V_i \omega_{Li} \bar{E}_{Li}}{\bar{\omega}_L}.
 \tag{A.5}$$

The average fluorescence energies by subshell are given in Table A.8. An analogous procedure can be used to calculate average Auger yields and energies.

The above calculation is not strictly accurate following a KLL Auger transition because the extra vacancy can significantly reduce (by 25% or 50%) certain Coster-Kronig transition rates, but it was used because it gives approximately correct results.

A.2.4 Shakeoff Electrons

The sudden change in atomic binding energies which occurs when a vacancy is produced by photoejection, fluorescence transitions and Auger transitions can cause “shakeoff” electrons to be lost from the atom. The probabilities of this occurring in neon, argon, krypton and xenon are given by Carlson and Nestor [84]. The probability can be quite high, e.g. 20% after following photoejection of a K electron, but the shakeoff electrons come almost entirely from the valence shell and have energies less than 0.05 keV.

The effect of shakeoff is that the photoelectron, Auger electron, or fluorescence photon which produced the shakeoff electron has $\Delta E = E_s + E_{B_s}$ less energy than if the shakeoff had not occurred, where E_s is the energy of the shakeoff electron and E_{B_s} was its binding energy. Typically ΔE is less than 0.1 keV, so shakeoff electrons can generally be ignored.

Appendix B

Modelling the Intrinsic Spatial Resolution of a Xenon Detector

The simulation of the RMS resolution of a xenon detector was based on a model of the production of the primary ionization cloud by the photoelectric absorption of an x ray. Each of the approximations made will be assigned a capital letter.

The photoelectron and all species emitted in the relaxation cascade are assumed to be emitted isotropically (A). For each emitted species, the important parameters are 1) the distance Δ from the initial interaction point to the centre of the charge cloud produced by that species, and 2) the energy E_{Δ} of that species.

The appropriate value to use for Δ is the mean free path λ for fluorescence photons, and the mean ionization range δ calculated as $0.6R_e$ (see Equation 2.15) for photoelectrons and Auger electrons. Values of λ and δ are given in Tables 2.1 and 2.2 for Auger electrons and fluorescence photons. The energies of photoelectrons are calculated using Equation 2.12 while the energies of Auger electrons and fluorescence photons are given in Figure 2.4 as well as in Appendix A.

The distance ρ by which the total charge cloud is shifted by the emission of a particular species i is

$$\rho = \Delta \frac{E_{\Delta}}{E_{ab}}. \quad (\text{B.1})$$

where E_{ab} is the total energy deposited in the detector.

For each cascade end point (indicated by a terminal node in Figure 2.4) following a

K photoabsorption there will have been one photoelectron emitted, one K fluorescence photon or K Auger electron emitted, and one L fluorescence photon or L Auger electron emitted. The net value of ρ_i for each end point i is approximated to be the maximum out of the three emissions (B), though K fluorescence is not included because it is assumed to escape from the detector and not contribute to E_{ab} (C). In cases where the end point is an L fluorescence photon, two ρ_i values ρ_{ia} and ρ_{ib} are calculated. The value ρ_{ia} is for the escape of the fluorescence photon and the value ρ_{ib} is for its recapture within the detector.

Similarly, following an L photoabsorption there will be one photoelectron and one L fluorescence photon or L Auger electron emitted. For an M or higher photoabsorption only the photoelectron is emitted (the model of the cascade ends at the L shell). This provides us with the distance ρ_i from the interaction location to the charge cloud centroid for each possible sequence of events. Next, the root mean square value σ_{rms} of ρ_i must be obtained.

In the simulation, the proportion b of L photoelectrons which escape is set to a value between 0 and 1. For a photon in the energy range $E_L < E < E_K$ the calculation goes as follows. Referring to Figure 2.4 on p. 25, only τ_L and τ_{MNO} are possible. First, the photoelectron energies $E_{-L} = E - 5.223 \text{ keV}$ and $E_{-MNO} = E - 1 \text{ keV}$ are calculated. Then, the average is taken by following the branches systematically, always taking the most probable branch first:

$$\begin{aligned} \sigma_{rms}^2 = & 0.7874 \left\{ 0.904 \left[\max\left(\delta(E_{\tau_L}) \frac{E_{\tau_L}}{E}, \delta(3.483 \text{ keV}) \frac{3.483 \text{ keV}}{E}\right) \right]^2 + \right. \\ & 0.096 \left((1 - b) \left[\max\left(\delta(E_{\tau_L}) \frac{E_{\tau_L}}{E}, \lambda(4.307 \text{ keV}) \frac{4.307 \text{ keV}}{E}\right) \right]^2 + \right. \\ & \left. \left. b \left[\delta(E_{\tau_L}) \frac{E_{\tau_L}}{E - 4.307 \text{ keV}} \right]^2 \right) \right\} + \\ & 0.2126 \left[\delta(\tau_{MNO}) \frac{E_{\tau_{MNO}}}{E} \right]^2 \end{aligned} \quad (B.2)$$

The calculation of σ_{rms} for a photon in the energy range $E > E_K$ is of the same form, but there are many more paths which must be considered.

Because the GMD has position readout along only one direction (refer to Equation 2.16), the final value for the RMS resolution of the GMD due to the xenon is

$$\sigma_{gas} = \frac{\sigma_{rms}}{\sqrt{3}}. \quad (B.3)$$

Appendix C

A Simple GMD Simulation

Several of the figures in this thesis (pp. 37.42.69.72.73) presented results from a GMD simulation. This appendix describes the simulation.

The simulation operates on an input set of photon interaction points x_j . For each x_j , it generates a normalized Gaussian

$$\frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{x'-x_j}{\sigma}\right)^2}, \quad (\text{C.1})$$

where σ is a parameter in the simulation. The Gaussian is then integrated over the anode bin intervals $[x'_i - 100 \mu\text{m}, x'_i + 100 \mu\text{m}]$ to obtain a simulated signal Q_i for each anode, where the x'_i are the locations of the anodes.

$$Q_i = \int_{(x'_i - 100\mu\text{m})}^{(x'_i + 100\mu\text{m})} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{x'-x_j}{\sigma}\right)^2} dx'. \quad (\text{C.2})$$

For one of the simulations (Figure 4.6 on p. 73) noise was added to the simulation at this point. This was done by adding $\sigma_Q \kappa_{ij}$ to the simulated signals Q_i , where κ_{ij} is a random number following a normal distribution with a mean of 0 and a variance of 1. The value of κ_{ij} was generated independently for each anode i and for each input photon interaction.

Finally, once the Q_i were generated, the centroid was calculated using either Equation 2.21 (the default) or one of the methods in Section 4.4. Figure C.1 shows two simulated signal distributions Q_i (with σ_Q set to zero) and the simulated charge

distributions which produced them. Figure C.1 also demonstrates that if the width of the charge distribution is too narrow compared to the anode pitch, then the calculated centroid $\hat{x}$ becomes a poor estimator of the mean x of the spatial charge distribution.

Figure C.1: Simulated events in the GMD for spatial charge distributions with (a) $\sigma = 150 \mu\text{m}$, and (b) $\sigma = 50 \mu\text{m}$. The ticks on the x' axis indicate the anode locations.

Appendix D

Measuring the Spatial Charge Distribution in the GMD

In Section 4.2.2 I referred to the charge diffusion measured for one of the data files. Figure D.1 shows the data from which the charge diffusion was determined. The detector was illuminated through a $20\text{ }\mu\text{m}$ slit, and the total charge collected on each anode channel (measured in ADC units) was measured and is plotted in Figure D.1. Fitting a Gaussian to the collected charge distribution gives a σ of $140\text{ }\mu\text{m}$, which arises primarily from charge diffusion but also from the ranges of the photoelectron and other secondaries emitted from the interaction site. Also shown in the figure is the line-spread function generated with the 3.4.5-channel weighted centroid method (Section 4.4.1) which is notably much finer than the collected charge distribution.

The Gaussian $A\exp(-\frac{1}{2}(x/\sigma)^2)$ was fit to the spatial charge distribution by integrating it over each anode bin interval $[x_i - 100\text{ }\mu\text{m}, x_i + 100\text{ }\mu\text{m}]$ and doing least-squares minimization to determine the A and σ which best matched the bin integrals to the anode data Q_i .

Figure D.1: Line-spread function (solid line) compared to collected charge distribution (dashed line) and the spatial charge distribution (dash-dotted line). The dotted line around the LSF is a Gaussian fit to the LSF. The two values of σ refer to the spatial charge distribution and to the Gaussian fit to the LSF.

References

- [1] E.A. Babichev, S.E. Baru, A.G. Khabakhpashev, G.M. Kolachev, V.V. Neustroev, Yu.N. Pestov, O.A. Ponomarev, G.A. Savinov, L.I. Shekhtman, A. Martinez-Davalos, R.D. Speller, and D.J. Miller. High pressure multiwire proportional and gas microstrip chambers for medical radiography. *Nucl. Instr. Meth.*, A360:271–276, 1995.
- [2] F. Arfelli, V. Bonvincini, G. Cantatore, L. Dalla Palma, M. Di Michiel, R. Longo, A. Olivo, S. Pani, D. Pontoni, P. Poropat, M. Prest, A. Rashevsky, G. Tromba, and A. Vacchi. A linear array silicon pixel detector: images of a mammographic test object and evaluation of delivered doses. *Phys. Med. Biol.*, 42:1565–1573, 1997.
- [3] G.C. Smith, D.E. Cox, and A.P. Jephcoat. X-ray position resolution in proportional chambers in the region of 100 μm (FWHM) above the xenon K-edge. *Nucl. Instr. Meth.*, A350:621–623, 1994.
- [4] A. Ochi and T. Tanimori. Recent status of T.I.Tech. imaging microstrip gas chamber. In D. Contardo and F. Sauli, editors, *Proceedings of the International Workshop on Micro-Strip Gas Chambers*, pages 59–64, November 1995. Lyons, France.
- [5] A. Martínéz-Dávalos, R.D. Speller, J.A. Horrocks, D.J. Miller, S.E. Baru, A.G. Khabakhpashev, O.A. Ponomarev, and L.I. Shekhtman. Evaluation of a new low-dose digital x-ray system. *Phys. Med. Biol.*, 38:1419–1432, 1993.

- [6] K.L. Yip, B.R. Whiting, T.E. Kocher, D.P. Trauernicht, and R.L. Van Meter. Understanding the relative sensitivity of radiographic screens to scattered radiation. *Med. Phys.*, 23:1727–1737, 1996.
- [7] D. Cavouras, I. Kandarakis, G.S. Panayiotakis, E.K. Evangelou, and C.D. Nomicos. An evaluation of the $\text{Y}_2\text{O}_3:\text{Eu}^{3+}$ scintillator for application in medical x-ray detectors and image receptors. *Med. Phys.*, 23:1965–1977, 1996.
- [8] I. Kandarakis, D. Cavouras, G. Panayiotakis, T. Agelis, C. Nomicos, and G. Giakoumakis. X-ray induced luminescence and spatial resolution of $\text{La}_2\text{O}_2\text{S:Tb}$ phosphor screens. *Phys. Med. Biol.*, 41:297–307, 1996.
- [9] J.W. Byng, N.F. Boyd, E. Fishell, R.A. Jong, and M.J. Yaffe. Automated analysis of mammographic densities. *Phys. Med. Biol.*, 41:909–923, 1996.
- [10] W. Zhao and J.A. Rowlands. X-ray imaging using amorphous selenium: Feasibility of a flat panel self-scanned detector for digital radiology. *Med. Phys.*, 22:1595–1604, 1995.
- [11] M. Säbel and H. Aichinger. Recent developments in breast imaging. *Phys. Med. Biol.*, 41:315–368, 1996.
- [12] A.B. Wolbarst. *Physics of Radiology*. Appleton & Lange, East Norwalk, Connecticut, 1993.
- [13] S. Webb, ed. *The Physics of Medical Imaging*. Institute of Physics Publishing, Bristol, 1995.
- [14] J. T. Dobbins III, David L. Ergun, Lois Rutz, Dean A. Hinshaw, Hartwig Blume, and Dwayne C. Clark. DQE(f) of four generations of computed radiography acquisition devices. *Med. Phys.*, 22:1581–1593, 1995.
- [15] T. Yu and J.M. Boone. Lens coupling efficiency: Derivation and application under differing geometrical assumptions. *Med. Phys.*, 24:565–570, 1997.

- [16] S. Hejazi and D.P. Trauernicht. System considerations in CCD-based x-ray imaging for digital chest radiography and digital mammography. *Med. Phys.*, 24:287-297, 1997.
- [17] L.E. Antonuk, Y. El-Mohri, J.H. Siewerdsen, J. Yorkston, W. Huang, V.E. Scarpine, and R.A. Street. Empirical investigation of the signal performance of a high-resolution, indirect detection, active matrix flat-panel imager (AMFPI) for fluoroscopic and radiographic operation. *Med. Phys.*, 24:51-70, 1997.
- [18] J.W. Boag. Xeroradiography. *Phys. Med. Biol.*, 18:3-37, 1973.
- [19] D.R. Dance. Chapter 2: Diagnostic Radiology with X-Rays, page 62. S. Webb, ed. *The Physics of Medical Imaging*. Institute of Physics Publishing, 1995.
- [20] G.H. Beute, M.J. Flynn, W.R. Eyler, E. Samel, E.L. Spitzamy, and C.J. Zy-lak. Chest radiographic quality: Comparison of asymmetric screen-film, storage phosphor, and selenium drum systems (abstract). *Radiology*, 201(P):480, 1996.
- [21] G.G. Reiker, R.M. Slone, P.K. Woodard, G. Fletcher, S.S. Sagel, and R.G. Jost. Technical and commercial evaluation of a commercial selenium-based digital chest imaging system (abstract). *Radiology*, 201(P):480, 1996.
- [22] J.A. Rowlands, W. Zhao, I. Blevis, D. Waechter, and Z. Huang. Digital radiogra-phy and fluoroscopy with a self-scanned flat-panel, amorphous selenium detector (abstract). *Radiology*, 201(P):525, 1996.
- [23] D.L. Lee, L.K. Cheung, and L.S. Jeromin. Imaging performance of a direct digital radiographic detector (abstract). *Radiology*, 201(P):327, 1996.
- [24] B.M. Moores, T. Dovas, B. Pullan, and R. Booler. A prototype digital iono-graphic imaging system. *Phys. Med. Biol.*, 30:11-20, 1985.
- [25] H.E. Johns and J.R. Cunningham. *The Physics of Radiology*. Charles C. Thomas, Springfield, Illinois, 4th edition, 1983.

- [26] M. Yaffe, A. Fenster, and H.E. Johns. Xenon ionization detectors for fan beam computed tomography scanners. *J. Comp. Assist. Tomogr.*, 1:419–428, 1977.
- [27] D.J. Drost and A. Fenster. A xenon ionization detector for scanned projection radiography: 95-channel prototype evaluation. *Med. Phys.*, 11:602–609, 1984.
- [28] D.J. Drost and A. Fenster. A xenon ionization detector for digital radiography. *Med. Phys.*, 9:224–230, 1982.
- [29] J.W. Motz and M. Danos. Image information content and patient exposure. *Med. Phys.*, 5:8–22, 1978.
- [30] A.D.A. Maidment and M.J. Yaffe. Analysis of signal propagation in optically coupled detectors for digital mammography: II. lens and fibre optics. *Phys. Med. Biol.*, 41:475–493, 1996.
- [31] F.A. DiBianca and M.D. Barker. Kinesthetic charge detection. *Med. Phys.*, 12:339–343, 1985.
- [32] E.A. Babichev, S.E. Baru, A.G. Khabakhpashev, G.M. Kolachev, O.A. Ponomarev, G.A. Savinov, and L.I. Shekhtman. Digital radiographic device, based on MWPC with improved spatial resolution. *Nucl. Instr. Meth.*, A323:49–53, 1992.
- [33] J.E. Bateman, M.W. Waters, and R.E. Jones. Spatial resolution in a xenon filled MWPC x-ray imaging detector—a computing physics approach. *Nucl. Instr. Meth.*, A135:235–249, 1976.
- [34] S.E. Baru, A.G. Khabakhpashev, I.R. Makarov, G.A. Savinov, L.I. Shekhtman, and V.A. Sidorov. Digital x-ray imaging installation for medical diagnostics. *Nucl. Instr. Meth.*, A238:165–169, 1985.
- [35] F. Angelini, R. Bellazzini, A. Brez, M.M. Massai, and M.R. Torquati. Bone densitometry with a high-speed, high-resolution MWPC. *Nucl. Instr. Meth.*, A283:423–430, 1989.

- [36] A. Oed. Position-sensitive detector with microstrip anode for electron multiplication with gases. *Nucl. Instr. Meth.*, A263:351–359, 1988.
- [37] F. Angelini, R. Bellazzini, L. Bosisio, A. Brez, M.M. Massai, A. Perret, G. Spandre, and M.R. Torquati. A microstrip gas chamber with true two-dimensional and pixel readout. *Nucl. Instr. Meth.*, A323:229–235, 1992.
- [38] F. Angelini, R. Bellazzini, A. Toropin, M. Bozzo, A. Brez, M.M. Massai, R. Raffo, G. Spandre, and M. Spezziga. A large area, high gain micro-gap chamber. *Nucl. Instr. Meth.*, A362:273–276, 1995.
- [39] S.F. Biagi, J. Bodas, D. Duxbury, E. Gabathuler, T.J. Jones, and S. Kiourkos. First experimental results from a microdot gas avalanche detector integrated into a silicon wafer. *Nucl. Instr. Meth.*, A366:76–78, 1995.
- [40] J. Kemmer. Improvement of detector fabrication by the planar process. *Nucl. Instr. Meth.*, 226:89–93, 1984.
- [41] R. Brenner, R. Harr, A. Rudge, D. Santos, J. Straver, P. Weilhammer, A. Czerwamak, S. Gadomski, M. Turala, V. Bonvicini, W. Kucewicz, S. Masciocchi, G. Vegni, A. Peisert, J. Ardelan, A. Hrisoho, K. Troung, F. Couchot, C. Colledani, W. Dulinski, D. Husson, A. Lounis, N. Mayet, M. Schaeffer, R. Turchetta, A. Smith, R. Apsimon, P. Seller, M. Tyndel, M. Aalste, I. Hietanen, J. Lindgren, K. Osterberg, R. Orava, C. Ronnqvist, T. Tuuva, and M. Voutilainen. Measurement of the spatial resolution of double-sided double-metal AC-coupled silicon microstrip detectors. *Nucl. Instr. Meth.*, 326:189–197, 1993.
- [42] F. Arfelli, G. Barbiellini, V. Bonvicini, A. Bravin, G. Cantore, E. Castelli, M. Di Michiel, R. Longo, A. Olivo, S. Pani, D. Pontoni, P. Poropat, M. Prest, F. Tomasini, A. Vacchi, and G. Tromba. A pixel-like matrix for digital mammography. *Nucl. Instr. Meth.*, A380:402–405, 1996.
- [43] F. Arfelli, G. Barbiellini, G. Cantore, E. Castelli, L. Dalla Palma, M. Di Michiel, R. Longo, P. Poropat, R. Rosei, M. Sessa, G. Tromba, and A. Vacchi. Silicon

- detectors for synchrotron radiation digital mammography. *Nucl. Instr. Meth.*, A360:283–286, 1995.
- [44] S.C. Taylor. Performance of gas microstrip detectors constructed on thin plastic substrates. MSc thesis, Carleton University, Ottawa, 1994.
 - [45] G.C. Stuart. Gas Microstrip Detectors on Thin Plastic Substrates. PhD thesis, Carleton University, Ottawa, 1995.
 - [46] M.S. Dixit, F.G. Oakham, J.C. Armitage, J. Dubeau, D. Karlen, G.C. Stuart, S.C. Taylor, I. Shipsey, E. Johnson, and A. Greenwald. Gas microstrip detectors on resistive plastic substrates. *Nucl. Instr. Meth.*, A348:365–371, 1994.
 - [47] P.C. Johns, J.C. Armitage, M.S. Dixit, J. Dubeau, D. Karlen, and F.G. Oakham. Gas microstrip detectors for digital x-ray imaging. In *Conference Proceedings*, pages 143–144. Canadian Organization of Medical Physicists, June 1995, Montreal.
 - [48] M.S. Dixit, J.C. Armitage, D. Bouius, L. Diaconescu, J. Dubeau, M. Grabari, P.C. Johns, D. Karlen, and F.G. Oakham. Digital x-ray imaging using gas microstrip detectors. In *IEEE Nuclear Science Symposium and Medical Imaging Conference Record*, pages 1597–1601, 1995.
 - [49] D.G. Gobbi, J.C. Armitage, M.S. Dixit, J. Dubeau, P.C. Johns, D. Karlen, and F.G. Oakham. Development of gas microstrip detectors for digital radiography (abstract). *Radiology*, 201(P):327, 1996.
 - [50] D.G. Gobbi, J.C. Armitage, M.S. Dixit, J. Dubeau, P.C. Johns, D. Karlen, and F.G. Oakham. Photon-counting radiography with xenon gas microstrip detectors. In *Conference Proceedings*, pages 31–33. Canadian Organization of Medical Physicists, July 1997, Charlottetown, PEI, Canada.
 - [51] P.C. Johns, J.C. Armitage, M.S. Dixit, J. Dubeau, D.C. Bouius, D.G. Gobbi, D. Karlen, and F.G. Oakham. Development of gas microstrip detectors for digital

- x-ray imaging. In *Conference Proceedings*, pages 255–256. Canadian Organization of Medical Physicists, June 1996, Vancouver.
- [52] M.S. Dixit, J.C. Armitage, J. Dubeau, D.G. Gobbi, P.C. Johns, D. Karlen, F.G. Oakham, and A.J. Waker. Development of gas microstrip detectors for digital x-ray imaging and radiation dosimetry. In *IEEE Instrumentation and Measurement Technology Conference Record*, pages 1357–1360, 1997.
 - [53] F.P. Santos, T.H.V.T. Dias, A.D. Stauffer, and C.A.N. Conde. Variation of energy linearity and w value in gaseous xenon radiation detectors for X-rays in the 0.1 to 25 keV range: a Monte Carlo simulation study. *Nucl. Instr. Meth.*, A307:341–346, 1991.
 - [54] F. Sauli. Principles of operation of multiwire proportional and drift chambers. Report CERN 77-09, European Organization for Nuclear Research, 1977.
 - [55] H.H. Barrett and W. Swindell. *Radiological Imaging: The Theory of Image Formation, Detection and Processing*, volume 1. Academic Press, New York, 1981.
 - [56] R. Birch and M. Marshall. *Catalogue of Spectral Data for Diagnostic X-rays*. Hospital Physicists' Association, London, 1979.
 - [57] E.F. Plechaty, D.E. Cullen, and R.J. Howerton. Tables and graphs of photon interaction cross sections from 1.0 keV to 100 MeV derived from the LLL evaluated nuclear data library. Report UCRL-50400 Vol. 6 Rev. 1, Lawrence Livermore Laboratory, 1975.
 - [58] T.H.V.T. Dias, F.P. Santos, A.D. Stauffer, and C.A.N. Conde. Monte Carlo simulation of x-ray absorption and electron drift in gaseous xenon. *Phys. Rev. A*, 48:2887–2902, 1993.
 - [59] D. Halliday and R. Resnick. *Fundamentals of Physics*, page A9. John Wiley & Sons, 3rd edition, 1988.

- [60] S.F. Biagi. A multiterm Boltzman analysis of drift velocity, diffusion, gain and magnetic-field effects in argon-methane-water-vapour mixtures. *Nucl. Instr. Meth.*, A283:716–722, 1989.
- [61] A. Peisert and F. Sauli. Drift and diffusion of electrons in gases: A compilation. Report CERN 84-08. European Organization for Nuclear Research, 1984.
- [62] G.F. Knoll. *Radiation Detection and Measurement*. John Wiley & Sons, New York, 2nd edition, 1989.
- [63] H. Helm. The mobilities of atomic krypton and xenon ions in the $^2P_{1/2}$ and $^2P_{3/2}$ state in their parent gas. *J. Phys. B*, 9:2931–2943, 1976.
- [64] E.A. Mason and E.W. McDaniel. *Transport Properties of Ions in Gases*. John Wiley & Sons, New York, 1988.
- [65] R. Bouclier, M. Capeáns, M. Hoch, G. Million, L. Ropelewski, F. Sauli, and T. Temmel-Ropelewski. High rate operation of micro-strip gas chambers. *IEEE Trans. Nucl. Sci.*, 43:1220–1226, 1996.
- [66] Yu.N. Pestov and L.I. Shekhtman. Influence of the bulk resistivity of glass with electronic conductivity on the performance of microstrip gas chamber. *Nucl. Instr. Meth.*, A338:368–374, 1994.
- [67] R. Mutikainen. Letter returned to Madhu Dixit with GMD prints made by VTT, April 18, 1996.
- [68] F. Sauli. Development of microstrip gas chambers for radiation detection and tracking at high rates: Final status report. Report CERN/LHCC 96-18. European Organization for Nuclear Research, 1996.
- [69] T. Zimmerman. A high-speed, low noise ASIC preamplifier for silicon strip detectors. *IEEE Trans. Nucl. Sci.*, 37:439–443, 1990.
- [70] K. Lau and J. Pyrlik. Optimization of centroid-finding algorithms for cathode strip chambers. *Nucl. Instr. Meth.*, A366:298–309, 1995.

- [71] C. Budtz-Jørgensen, A. Bahnsen, C. Olesen, M.M. Madsen, P. Jonasson, H.W. Schnopper, and A. Oed. Microstrip proportional counters for X-ray astronomy. *Nucl. Instr. Meth.*, A310:82–87, 1991.
- [72] L.I. Shekhtman. High pressure gas avalanche chambers for medical radiology. *Physica Medica*, IX:117–122, 1994.
- [73] F. Angelini, R. Bellazzini, A. Brez, M.M. Massai, G. Spandre, and M.R. Torquati. A microstrip gas avalanche chamber with two-dimensional readout. *Nucl. Instr. Meth.*, A283:755–761, 1989.
- [74] J.F.C.A. Veloso, J.A.M. Lopes, J.M.F. dos Santos, and C.A.N. Conde. A microstrip gas chamber as a VUV photosensor for a xenon gas proportional scintillation counter. *IEEE Trans. Nucl. Sci.*, 43:1232–1236, 1996.
- [75] T.H.V.T. Dias, F.P. Santos, A.D. Stauffer, and C.A.N. Conde. The Fano factor in gaseous xenon: a Monte Carlo calculation for X-rays in the 0.1 to 25 keV range. *Nucl. Instr. Meth.*, A307:341–346, 1991.
- [76] R. Bouclier, M. Capeáns, C. Garabatos, G. Manzin, G. Million, L. Ropelewski, F. Sauli, L. Shekhtman, K. Silander, and T. Temmel-Ropelewski. Ageing of microstrip gas chambers: problems and solutions. *Nucl. Instr. Meth.*, A381:289–319, 1996.
- [77] R. Bouclier, C. Garabatos, G. Manzin, G. Million, F. Sauli, T. Temmel, and L. Shekhtman. Ageing studies with microstrip gas chambers. *Nucl. Instr. Meth.*, A348:109–118, 1994.
- [78] S. Kiourkos, S.F. Biagi, T.J.V. Bowcock, T.J. Jones, and J.N. Jackson. Comparison of experimental measurements and electrostatic simulations of keystone geometry microstrip gas chambers. *Nucl. Instr. Meth.*, A348:351–355, 1994.
- [79] P.C. Johns, D.J. Drost, M.J. Yaffe, and Aaron Fenster. Dual energy mammographic imaging. *Proc. SPIE*, 419:201–208, 1983.

- [80] J.H. Scofield. Relativistic Hartree-Slater values for K and L x-ray emission rates. *At. Data Nucl. Data Tables*, 14:121–137, 1974.
- [81] M.H. Chen, B. Crasemann, and H. Mark. Relativistic radiationless transition probabilities for atomic K - and L -shells. *At. Data Nucl. Data Tables*, 24:13–37, 1979.
- [82] W. Bambynek, B. Crasemann, R.W. Fink, H.-U. Freund, H. Mark, C.D. Swift, R.E. Price, and P. Venugopala Rao. X-ray fluorescence yields, Auger, and Coster-Kronig transition probabilities. *Rev. Mod. Phys.*, 44:716–813, 1972.
- [83] K.-N. Huang, M. Aoyagi, M.H. Chen, B. Crasemann, and H. Mark. Neutral-atom electron binding energies from relaxed-orbital relativistic Hartree-Fock-Slater calculations $2 \leq Z \leq 106$. *At. Data Nucl. Data Tables*, 18:243–291, 1976.
- [84] T.A. Carlson and C.W. Nestor, Jr. Calculation of electron shake-off probabilities as the result of x-ray photoionization of the rare gases. *Phys. Rev. A*, 8:2887–2894, 1973.

IMAGE EVALUATION TEST TARGET (QA-3)

APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989

© 1993, Applied Image, Inc., All Rights Reserved