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Gas Microstrip Detectors on Thin Plastic Substrates

by

Gregory C. Stuart B.A.Sc., M.A.Sc., P. Eng.

**A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of
Doctor of Philosophy**

**Ottawa-Carleton Institute for Physics
Department of Physics, Carleton University
Ottawa, Ontario, Canada
September, 1995**

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**Gas Microstrip Detectors
on Thin Plastic Substrates**

submitted by

Gregory C. Stuart B.A.Sc., M.A.Sc.

in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

Chair, Department of Physics

Thesis Supervisor

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Carleton University

Date 15.9.95

Abstract

Gas microstrip detectors were built on two thin ($100\text{ }\mu\text{m}$) plastic substrates, Tedlar and ion-implanted Upilex, and their performance characterized in the laboratory and during beam tests. Gas gain, energy resolution, spatial resolution, and timing resolution were obtained. A novel method of measuring electron drift velocity using the Upilex detectors and angled ionizing particle tracks determined a velocity of $36 \pm 2\text{ }\mu\text{m/ns}$ at 4 kV/cm for a 90-10 argon-isobutane gas mix.

A detailed Monte Carlo simulation of the operation of the detectors was performed, and the results were in good agreement with the experimental results. The simulation, which included readout via fast electronics, was used to understand fundamental detector physics and predict the performance of gas microstrip detectors in the ATLAS inner tracker.

The experimental and simulation results demonstrated the suitability of gas microstrip detectors for use in tracking at high-luminosity next-generation colliders and in medical physics imaging.

Acknowledgements

I would like to thank John Armitage for the supervision and support provided throughout the course of this work. Phillippe Gravelle, Ernie Neuheimer, and Karl Miels, of the Centre for Research in Particle Physics (CRPP), and Barbara Ellspermann and Peter Hermann, of the Science Technology Centre (STC), provided invaluable technical assistance. Thanks also go to CRPP scientists and faculty of the Carleton Physics Department, in particular Madhu Dixit, Gerald Oakham, Dean Karlen, and Penny Estabrooks, and fellow graduate students and research associates, especially Steve Taylor and Jacques Dubeau, for their assistance and encouragement.

Steve Biagi of Liverpool University generously provided two programs which were the basis for the Monte Carlo simulations. Alan Barney, Bill Jack, Wade Hong, and Jim Carleton were very helpful in terms of computer hardware and software.

The funding of this research by grants from the Natural Sciences and Engineering Research Council (NSERC) is appreciated. In addition, the personal financial support provided by an NSERC Postgraduate Scholarship and two Ontario Graduate Scholarships is gratefully acknowledged.

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Chapter 1

Introduction

Gas microstrip detectors built on thin plastic substrates were developed for tracking charged particles in high-energy physics experiments, and as X-ray detectors in medical imaging applications. These detectors are also known as MicroStrip Gas Counters (MSGCs), and this acronym will be used throughout the thesis. Figure 1.1 shows a MSGC whose structure and operation will be discussed in detail in Chapter 3. A charged particle or X-ray ionizes the gas and signals are produced on the electrodes.

Figure 1.1: Structure of gas microstrip detector.

The improved performance of gas microstrip detectors, compared to earlier types of gaseous detectors, has motivated world-wide MSGC research activity over the past few years. MSGCs are among the most important position-sensitive detectors now under development. The work described in this thesis was done at the Physics Department of Carleton University and the Center for Research in Particle Physics

(CRPP), starting in the fall of 1991 with the first operation of a plastic MSGC in North America.

As described in Chapter 4 glass masks and photolithography were used to produce MSGC prints on plastic substrates at firms in Canada and the United States. A collaborative effort with industry resulted in the required print quality and in optimized metallizations. The availability of high-quality plastic MSGC prints allowed for the characterization of the MSGCs, including a survey of their performance as a function of electrode geometry, operating voltage, gas mixture, incident flux, and substrate resistivity.

X-rays from radioactive sources and a X-ray generator were used in the laboratory to investigate the operation of the plastic MSGCs. The detectors were also tested in charged particle beams. Pre-test and post-test inspection of the MSGC prints using video and scanning-electron microscopy provided insight into damage mechanisms.

A detailed MSGC simulation program was modified and adapted for plastic gas microstrip detectors combined with fast electronic readout. The simulations confirmed experimental results and improved understanding of the physics of these detectors.

1.1 Motivation

Investigation of the performance and operation of plastic MSGCs requires solving the engineering problems associated with their production and testing as well as consideration of the specific applications. MSGCs offer the ability to handle higher incident fluxes than previous gaseous detectors. As with earlier types of particle detectors, high-energy physics (HEP) requirements have motivated their development and funded most of the MSGC research.

The interest in MSGCs is focused towards their application in charged-particle tracking at high-luminosity, next-generation colliders, as well as for upgrades to existing collider experiments. Proton colliders, with beam energies of several TeV,

have the potential to discover the Higgs particle and open new energy scale frontiers. The Higgs particle is predicted by the Standard Model which is the model describing all the fundamental particles and their interactions. Recent results [1] [2] from the Fermilab TeVatron, currently the world's highest energy collider, indicate that the top quark has been discovered at a mass of $180 \text{ GeV}/c^2$. The Higgs particle is now the most important prediction of the Standard Model which has yet to be experimentally confirmed. Either the Higgs will be found, or new physics beyond the Standard Model will be required. This makes the search for the Higgs particle the next task at hand for the high-energy physics community.

The development of MSGCs has been driven primarily by the requirements of this Higgs particle search at new, large proton colliders. Table 1.1 gives the details of these high-energy, high-luminosity proton colliders, and Table 1.2 gives some information on the use of MSGCs in the associated detector facilities. The ATLAS

	LHC	SSC
location	CERN	Texas
completion date	2008	cancelled
beam energy	7 TeV	20 TeV
luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	10^{34}	10^{33}
bunch period (ns)	25	16
beam frequency (MHz)	40	63.5
interaction regions	3	2

Table 1.1: Next-generation proton colliders.

and CMS detectors, being designed for the Large Hadron Collider (LHC) at CERN, are the most extensive proposed uses of MSGCs, and significant research effort is required for these two projects. CERN, the European Laboratory for Particle Physics, is located on the French-Swiss border outside of Geneva. Local MSGC research has been directed to the SDC and ATLAS detectors, which are described later in this chapter and are discussed in greater detail in Chapter 2. Fields outside of experimental particle physics will also benefit from the development of MSGCs [3] [4]. The medical physics community has shown interest in gas

	ATLAS	CMS	SDC
location	LHC	LHC	SSC
MSGC tiles	6400	19800	3250
MSGC channels	1.5×10^6	1.3×10^6	1.5×10^6
typical flux ($\text{mm}^{-2}\text{s}^{-1}$)	10^4	10^4	10^5

Table 1.2: MSGCs in next-generation detectors.

microstrip detectors for application to X ray imaging and microdosimetry. Low-energy X-rays, such as those used in mammography, can be efficiently detected with specialized MSGCs, and high-resolution digital images can be obtained at lower radiation doses than by using conventional film techniques.

1.2 History

Gas microstrip detectors represent a major improvement over their immediate forebears, namely MultiWire Proportional Counters (MWPCs). The MSGC notation has become the standard acronym within high-energy physics, and is favoured over the alternative, GMD, because the former is closer to the familiar MWPC. The development of the MWPC [5] facilitated most of the important achievements over the last twenty five years of high-energy physics, and its significance was confirmed by the 1992 Nobel Prize in Physics awarded to its pioneer, Georges Charpak. MWPCs are major components of the tracking systems at many existing high-energy physics experiments. Gas detectors of all sorts, MWPCs, drift chambers, straw tubes, time-projection chambers etc., combine large area capability with good radiation hardness.

MSGCs offer improved performance compared to MWPCs in terms of criteria such as rate capability, spatial resolution, timing resolution, and lifetime. They can be fabricated in large areas as radiation-hard, precision-tracking detectors. The original research by Oed [6] and his group at the Institut Laue-Langevin (ILL) in Grenoble, France, in 1988, was motivated by the need for a high-resolution particle detector. The ILL group produced MSGCs fabricated on 500 μm thick

glass substrates.

MSGC research and development has been substantial over the past few years, with devices being constructed using a variety of geometries and substrates. Research on MSGCs has had two primary directions which have been pursued in parallel over the years since 1988. One effort has been to use relatively standard, glass-like substrates and concentrate on large-area devices suitable for use at low to moderate particle fluxes. The second effort has been to find alternative substrates and resistivity-modification techniques which, as discussed in Chapter 3, are required to operate MSGCs in high-flux environments. Both topics have made significant progress, but MSGCs are only now, seven years after their introduction, starting to be produced as devices suitable for many proposed applications. This thesis reports the results of research on plastic MSGCs which are part of the second general MSGC research theme.

It is informative to look at the history of MSGC research. In terms of glass-like substrates notable early success was achieved at INFN in Italy [7] [8]. The group there also produced large-area MSGCs on ion-implanted silicon dioxide [9]. The first applied use of MSGCs in a high-energy physics experiment was in 1991 as part of the fixed-target experiment NA12 (GAMS) at the CERN Super Proton Synchrotron (SPS). This experiment used 1100 channels of 200 μm pitch glass MSGCs [10].

The first MSGCs produced on plastics were made in 1990, in Germany, on polyester and polyimide [11]. The latter device was a small 200 μm pitch detector built on 50 μm thick Kapton with copper electrodes. It suffered severe gain instability attributed, as will be described in section 3.1.1, to charging of the untreated high-resistance Kapton surface. The MSGC group at CERN, led by Fabio Sauli, investigated detectors built on plastics such as Tedlar and Kapton, and it was their early results which spurred the initial activity of our group.

The research described here was undertaken in the context of three different collaborative efforts, namely RD-28, SDC, and ATLAS. Personnel from both

the Carleton Physics Department and the CRPP are, or have been, members of these three collaborations. There have been other research groups, participating in the collaborations, who have investigated MSGCs fabricated on plastics and other alternative substrates. This includes groups at CERN, Texas A+M, Purdue, Montreal, and TRIUMF. Plastic MSGC research is only a subset of the field, with more effort by the collaborations focussing on a variety of types of glass and glass-like substrates. Both plastic and glass MSGC development has progressed to the point where they are now being considered as candidates for large-scale use at the LHC.

1.2.1 RD-28

The RD-28 collaboration was approved by the CERN Research Board in 1992 for research on gas microstrip detectors. As part of RD-28 local efforts at Carleton-CRPP concentrated on the production of MSGCs on plastic substrates, and on the development of methods of tailoring the resistivity of these substrates in order to achieve high-flux capability. The RD-28 final report [12] was presented at CERN in January 1995, and some of the results given in this thesis were incorporated in the sections describing plastic MSGCs.

1.2.2 SDC

The Solenoidal Detector Collaboration (SDC) [13] was working on the design of a detector facility for the Superconducting Super Collider (SSC) up to the cancellation of the project in October 1993. The SSC was going to be a 20 TeV proton-proton collider constructed in an 84 km circumference tunnel in Waxahachie, Texas. Much of the early research on gas microstrip detectors, and certainly one of the principal focuses for the Carleton-CRPP instrumentation group from 1991 to 1993, was directed to the development of MSGCs for use in this large solenoidal detector. The MSGCs were going to be used in the forward tracking regions, and were configured as tiles covering large disks on either side on the inter-

action point. Further details on the MSGCs in the SDC detector will be presented in section 2.2.1 of the following chapter.

1.2.3 ATLAS

The Advanced Toroidal LHC ApparatuS (ATLAS) detector is the largest of three experiments being designed for the LHC which is scheduled to be running at full 7 TeV beam energy in 2008. The LHC will be constructed in the existing 27 km circumference LEP collider tunnel. ATLAS is one of the two detectors which will be used to study proton-proton interactions at the LHC, and, like its colleague the Compact Muon Solenoid (CMS) detector, includes the use of gas microstrip technology. The ATLAS collaboration consists of 140 different institutions, and over 1500 individual members. The LHC will also be able to collide lead ions at a luminosity of $10^{27} \text{ cm}^{-2}\text{s}^{-1}$, and the ALICE heavy-ion detector will be constructed for this purpose.

Since the cancellation of the SSC in 1993, the research of the Carleton-CRPP MSGC group has been motivated to a large part by our participation in the ATLAS project. The MSGCs in ATLAS will be used in the inner tracking system and, similar to the SDC, configured as tiles on large hollow-wheel structures. The operating environment for the MSGCs in ATLAS will be discussed in greater detail in section 2.2.2 of the next chapter, and Chapter 7 includes results of simulations performed on the ATLAS MSGCs.

1.3 Thesis Outline

This thesis consists of a total of eight chapters and two appendices. Subsequent to this introduction Chapter 2 puts MSGCs in context by describing alternative detection technologies with emphasis on precision charged-particle tracking. In addition the chapter discusses the detailed requirements for gas microstrip detectors used at SDC, ATLAS, and in high-resolution medical imaging.

Chapter 3 will provide the theory necessary for understanding the operation

of gas microstrip detectors. Important electron-transport theory required for the numerical simulation will be presented, as well as a discussion of the interactions with different types of ionizing radiation.

Chapter 4 describes the production of the plastic MSGC prints. Methods for their inspection and connection are presented, as are some important findings related to their ultimate behaviour as detectors.

Chapter 5 reports the results obtained when the plastic MSGCs were tested in the laboratory with radioactive sources and an X-ray generator. These results show the differences between MSGCs based on surface conduction, namely ion-implanted Upilex, and those built on a bulk conductor, namely Tedlar.

Chapter 6 gives results from four beam tests during which the plastic MSGCs were operated in particle beams at CERN and TRIUMF. The fast electronics used to readout the MSGCs are discussed in some detail because they were important both in terms of the experimental results and the numerical simulations.

Chapter 7 discusses the computer simulations of the MSGCs and presents their results. The various programs used are described and the results from the simulations are compared to real data.

Chapter 8 summarizes the thesis and gives the important conclusions that have been arrived at as a result of this research. In addition, recommendations are given for the direction of future activities.

Chapter 2

Alternative Technologies and Operating Environments

This chapter consists of two sections. The first section provides a description of some of the detection technologies which could be used as alternatives to MSGCs. The choice of detector type includes consideration of cost, resolution, power dissipation, and radiation hardness. The second section presents three different environments where MSGCs will be expected to operate.

2.1 Alternative Technologies

In order to understand the potential benefits of MSGCs it is necessary to view them in terms of other types of detectors. The multiwire proportional counter will be described since the limitations of this type of detector provided the initial motivation for the development of MSGCs. Two types of solid-state detectors, silicon and gallium arsenide, will then be discussed, followed by scintillating fibres (Sci-Fi) and straw-tubes. It is important to keep in mind that these detection technologies are often complementary rather than competitive. This is certainly true in HEP applications where experiments make use of several different types of detectors in combination. For example, as shown in section 2.2.2, the tracking system of the ATLAS detector potentially includes gas microstrip, straw-tube, silicon, and gallium arsenide detectors. Silicon microstrips remain the detector

of choice for many high-precision tracking applications. However MSGCs fill the existing gap between silicon strips and the lower-resolution tracking provided by straw tubes and wire chambers.

Table 2.1 summarizes the different types of detectors which are discussed in this chapter. The table lists the typical size of the signal, to the nearest order of magnitude and given as the number of electrons produced by a minimum-ionizing particle, the noise, the spatial resolution, and the read-out element spacing.

	signal (e^- /MIP)	noise (e^-)	σ_{space} (μm)	element size (μm)
straw	10^4	10^3	150	4000
MWPC	10^5	10^3	100	1000
MSGC	10^5	10^3	40	200
MGC	10^5	10^3	50	200
Si strip	10^4	10^3	10	50
Si pixel	10^4	10^2	20	50×100
GaAs pixel	10^4	10^2	20	75×100
Sci-Fi	10	1	20	50

Table 2.1: Characteristics of different detector technologies.

2.1.1 MultiWire Proportional Counter

Figure 2.1 shows a cross-section of a MWPC. A plane of anode wires is located at the center of a gas volume which is enclosed on either side by a cathode plane. The anodes are kept at positive high voltage relative to the cathode planes. The detection mechanism is the same in all gas detectors (including MSGCs). It consists of ionization, electron drift, and avalanche in the high electric fields around the anodes. Signals are induced on the anodes by the avalanche ions as they move to the cathodes. These processes will be described in detail in Chapter 3 where MSGCs are discussed.

Figure 2.1: MWPC cross-section.

Two limitations of the MWPC are inherent to its geometry. Firstly, there is a minimum wire spacing imposed by mechanical constraints. The anode wires must be stretched tightly to prevent displacements due to the electrostatic forces of repulsion between adjacent wires. Secondly, all the ions created in the gas avalanches around the anode wires must drift to the cathode planes. The normal electric field in the MWPC is not fully regained until these ions reach the cathodes, which will typically take between 10 and 100 μs . The reduction in the effective electric field decreases the signal magnitude. Ultimately this space charge limits the maximum flux which any gas detector can efficiently detect. MWPCs are rate-limited to about $10^4 \text{ mm}^{-2}\text{s}^{-1}$, and this, combined with the spacing of the anodes, makes them inadequate for many new high-energy physics applications. For instance space charge in a 1 mm MWPC limits the maximum detected rate to $3 \times 10^4 \text{ mm}^{-2}\text{s}^{-1}$ [14].

2.1.2 Solid-State Detector

Solid-state detectors are built using two semiconductor materials, silicon and gallium arsenide, whose relevant properties are listed in Table 2.2. Devices fabricated using silicon are widely used in high-energy physics, while those made on gallium arsenide are a more recent development.

	silicon	gallium arsenide
band gap energy (eV)	1.11	1.43
pair creation energy (eV)	3.6	4.2
MIP energy loss (MeV/mm)	0.39	0.56
electron mobility ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)	1350	6700
hole mobility ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)	480	400
v_e at 3 keV/cm ($\mu\text{m}/\text{ns}$)	41	200
v_h at 3 keV/cm ($\mu\text{m}/\text{ns}$)	14	12
radiation length (cm)	9.4	2.3

Table 2.2: Properties of materials used in solid-state detectors.

Silicon Microstrip Detector

Silicon microstrip detectors, commonly referred to as silicon strips, have become a standard HEP detection technology [15] [16] [17] [18]. They are used primarily for precision tracking close to the interaction point and for vertex detection. Very high spatial resolution is possible with typical read-out pitches being from 20 to 50 μm .

Figure 2.2 shows a cross-section of a single-sided silicon microstrip detector which can be considered as a series of reverse-biased pn diodes.

Figure 2.2: Single-sided silicon microstrip detector.

The production process uses standard photolithographic techniques. An n -type silicon wafer, typically 300 μm thick, is doped to produce p^+ strips at the desired pitch. Metal electrodes are deposited on these strips to provide electrical connections. The rear surface of the wafer is made n^+ and coated with metal. Silicon microstrip detectors can also be made using a double-sided layout, where a segmented n^+ strip-electrode structure, at some angle with respect to the front-surface

pattern, is produced on the rear surface of the wafer. This provides two layers of particle detection without increasing the amount of material in the device.

A bias voltage, typically 100 V, depletes the silicon wafer below each of the p^+ strips. Charged particles travelling through the depleted regions produce electron-hole pairs which are collected on the electrodes. 3.6 eV is required to produce an electron-hole pair in silicon. This is an order of magnitude less than the ionization energy of a typical gas. However, unlike a gaseous detector, there is no multiplicative avalanche, and the signals in a silicon microstrip are somewhat smaller.

Silicon microstrip detectors, though more expensive, were considered as an alternative to MSGCs in both the SDC and ATLAS tracking systems. The present inclination is to favour silicon over MSGC technology in applications where both types of detector satisfy the technical requirements. This is due to the relative maturity of silicon compared to MSGCs. Silicon microstrips have been used by the HEP community for over ten years, while MSGCs are only now coming into large-scale use.

A serious concern with silicon microstrips is the damage which they suffer in high-radiation environments. For example the Fermilab E771 experiment used silicon microstrips which were subjected to exposures of 9.5×10^{11} particles mm^{-2} . The silicon near the beam axis deteriorated rapidly after an exposure of 2×10^{11} particles mm^{-2} and became completely inoperable at 6×10^{11} particles mm^{-2} [19]. The damage in the bulk silicon lattice is due to the displacements and transmutations induced by high-energy hadrons. There are also surface damage effects, where interface-trapped charges lead to increased leakage currents and reduced lifetime. Much silicon microstrip research is focussed on developing radiation-hard devices and studying the damage mechanisms.

Another important consideration with silicon is its radiation length, which is roughly equivalent to that of MSGCs produced on glass but is shorter than MSGCs on plastics. Radiation length is related to photon conversions and multiple scattering which degrade the performance of tracking systems. A short radiation

length material is less desirable than one with a long radiation length.

Silicon pixels are a variant of silicon microstrip detectors which consist of two-dimensional arrays of solid-state sensing elements. Each element can have its amplification electronics constructed within the silicon substrate itself, however most existing devices have separate read-out structures connected to the sense elements by indium bump contacts. Silicon pixels are more radiation resistant than their silicon strip counterparts, but are more expensive. The enhanced radiation hardness is due to the smaller cell size, with each pixel being of the order of $50\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$.

Gallium Arsenide Microstrip Detector

Recently solid-state microstrip detectors have been constructed using gallium arsenide (GaAs) rather than silicon as the semiconductor material. These GaAs devices offer the potential of much higher radiation resistance than silicon, but are still unproven in large-scale high-energy physics applications. They are under consideration for use in the precision tracking at ATLAS [20].

The larger band gap energy of gallium arsenide results in bulk generation currents up to 10^4 times less than in silicon devices. These bulk currents are directly related to the radiation exposure damage, so that GaAs can have greater radiation resistance than silicon. More energy is required to displace an atom in the GaAs crystal lattice compared to silicon. Two drawbacks of GaAs, with respect to silicon, are its shorter radiation length, by a factor of four, and its poor charge-collection efficiency due to the rapid trapping of holes.

2.1.3 Scintillating Fibre Detector

Scintillating fibre detectors make use of the improvements in optical fibre and photodetector technology made by the telecommunications industry. The detectors combine scintillator technology with optical fibre technology. They are attractive because of their speed and insensitivity to magnetic fields, however, like other detectors, they are subject to radiation damage.

The detector consists of arranged bundles of scintillating fibres each of which is readout by low-noise photodetectors located at the fibre ends. The fibre consists of an organic core, commonly polystyrene, doped with a scintillating agent, which is surrounded by a low refractive index cladding. The fibres are only doped with the scintillator in the active area and the lengths of the fibres outside this region are not scintillating. The cladding serves to contain the scintillation light by total internal reflection at the core-cladding interface. The diameter of the core is of the order of 50 μm while the cladding is approximately 5 μm thick.

A charged particle passing through the fibres generates visible and ultraviolet scintillation light which is transmitted down the fibres to the corresponding photodetectors. The light signal is small due to the short interaction path length, particularly when the particle does not pass through the full diameter of the fibre. Any scintillation light emitted at an angle greater than the critical angle is lost entirely. This small light signal is attenuated as it travels to the ends of the fibres due to absorption and losses at the core-cladding interface. The photodetectors at the ends of the fibre have to be extremely sensitive to detect the small number of photons which reach the ends.

The development of Visible-Light Photon Counter (VLPC) detectors made the Sci-Fi concept feasible. These detectors have a high quantum efficiency and ultra-low noise levels which permit them to handle signals which are only of the order of 5 to 10 photoelectrons in magnitude. In a tracking detector the photodetectors are located within strong magnetic fields which imposes additional requirements on their performance. The response time of the VLPCs is typically under 5 ns, and the spatial resolution of a scintillating fibre system will be of the order of the fibre diameter. Radiation damage is primarily in terms of the degradation of the optical transmission characteristics of the fibre. This results in reduced light intensity at the photodetectors.

2.1.4 Straw Tube Detector

Straw tubes are one implementation of “conventional” gas detector technology which provide for the coverage of very large tracking volumes at relatively low cost. The segmentation of the straw-tube geometry allows the devices to handle moderately high particle rates and, like MSGCs, they are radiation resistant. Straw tubes are used in regions where the track density is low but the data they provide aid pattern recognition during track finding.

Each straw tube is a long, single-wire cylindrical proportional tube with the diameter of the straw typically being 4 mm. The walls of the straw are made of thin, radiation-resistant material, often carbon-fibre reinforced Kapton. The signals are obtained from the central anode wires and include a pronounced ion tail since all the ions must drift over the entire radial distance from the anode wires to the tube walls. Electron arrival times in a straw tube span the radial drift distance.

With a careful choice of gas mixture, and fast electronics, the spatial resolution achievable is of the order of $150\text{ }\mu\text{m}$. The occupancy in the straw tubes in a high-luminosity environment like at the LHC is of concern. CF_4 -based gas mixes are often contemplated for straw tubes in these applications [13] [21] because of their high drift velocity.

2.1.5 MicroGap Counter

The type of MSGC detector described in this thesis, whose geometry is presented in the following chapter, represents the “standard” MSGC configuration. Even though this is a young field there have been important variations on the basic MSGC theme. One such variation will be discussed in detail since, in a sense, this can also be considered as an alternative to MSGCs. This variation is the Micro-Gap Counter(MGC) which takes the MSGC concept to its logical extreme and was proposed by the group at INFN in Italy. In the MGC structure, as illustrated in Figure 2.3, the anodes are supported on top of insulating strips on a conducting

plane which forms the cathode.

Figure 2.3: MGC built using (a) traditional and (b) self-aligned fabrication.

Typical dimensions for a 200 μm pitch MGC are an anode width of 10 μm , an insulator width of 15 μm , and an insulator thickness of 2 μm . The insulator is either SiO_2 or polyimide, and the most common substrate has been 500 μm thick quartz. Like a MSGC, there is a drift electrode enclosing the gas volume. With essentially no insulating surface between the anodes and the cathode the problem of surface charging, discussed in section 3.1.1, is solved. One drawback with the MGC is the large capacitance between the anodes and the cathode. This results in large signals being induced on the cathode and this cross-talk between neighbouring anodes degrades the spatial resolution.

MGCs are proposed for use in particle tracking at CMS as an alternative to MSGCs [22]. They have demonstrated a flux rate of $10^7 \text{ mm}^{-2} \text{ s}^{-1}$ with a 70-30 argon-DME gas mix, an energy resolution of 14.8% for 5.4 keV chromium X-rays, and a spatial resolution of 50 μm . MGCs have also been investigated for medical imaging applications.

MGC fabrication is more difficult than MSGCs, requiring mask alignment during the lithography. In traditional MGC fabrication, where structures as shown in Figure 2.3a are built, the masks used during the production of the insulating strips and the anodes must be kept in alignment to within a few microns over the entire active area. In the case of large devices, where the anodes are over 10 cm long, this requires precise angular alignment between the two masks. In contrast MSGCs require only one mask, and there are no alignment limitations. Recently “self-alignment” techniques have been used to produce MGCs. The anodes are supported on insulators of equal width, as shown in Figure 2.3b. The insulating

material must have a high dielectric strength since it must hold the high voltages between the anodes and the cathode without breakdown.

Ageing effects (see section 3.6) may be more severe in MGCs than in MSGCs due to their greater anode surface fields. MGC anode surface fields [23] are typically 2700 kV/cm, compared to the 400 kV/cm for a MSGC, and 130 kV/cm for a MWPC, as shown in Figure 2.4.

Figure 2.4: MWPC, MSGC, and MGC electric fields and equipotentials (adapted from [23]).

2.2 Operating Environments

Three different high-rate environments, suitable for MSGCs, are described in this section. The SDC experiment is presented since this was a challenging early application for plastic MSGC technology. Its requirements drove the development of ion-implanted polyimide as a MSGC substrate, and were the focus of initial Carleton-CRPP research activities. The specifications for the MSGCs in the SDC exceeded those for the ATLAS detector, whose environment will also

be described and which was more recently the subject of local MSGC research and development. Finally the requirements for a X-ray imaging mammographic detector are presented as an application outside the field of high-energy physics. Other possible applications for MSGCs include precision radiography for industrial non-destructive testing and microdosimetry.

2.2.1 SDC

The Solenoidal Detector Collaboration (SDC) [13] was working on the design of one of the two approved experiments for the SSC until its cancellation. MSGCs were going to be used for precision tracking in the Intermediate-angle Track Detector (ITD), shown in Figure 2.5. The Solenoidal Detector was to consist of a large, 2-Tesla, solenoidal magnet containing tracking detectors and surrounded by calorimeters and muon detectors. The purpose of tracking was to precisely measure the momenta of charged particles, emitted in the proton-proton interactions, by following the tracks of these particles as they were bent in the magnetic field. In addition the tracking detectors would check the vertex of the event and determine the point of entry into the calorimeters.

Figure 2.5: Solenoidal Detector.

The SDC tracking system, shown in Figure 2.6, was 8.5 m long with a 1.6 m radius. It consisted of an inner silicon tracker and an outer tracker. The outer

tracker consisted of a straw tube barrel tracker and the MSGC-based ITD [24] located in the end regions. Table 2.3 gives some details of the three different sub-systems. In terms of pseudorapidity, η , the MSGCs would cover the range $1.8 < |\eta| < 2.8$. Appendix A explains rapidity and pseudorapidity. Large values of pseudorapidity correspond to small angles with respect to the beam axis and interaction point. The SDC tracking system was designed to meet the requirement that the momentum resolution at a transverse momentum, $p_T = 1 \text{ TeV}/c$, was better than 16% at $\eta = 0$, and better than 60% at $\eta = 2.5$. An important

	silicon	straw tube	MSGC
pseudorapidity	$ \eta < 2.5$	$ \eta < 1.8$	$1.8 < \eta < 2.8$
channels	6.5×10^6	1.4×10^5	1.5×10^6
active region	17 m^2	40 m^3	93 m^2
element spacing	$50 \mu\text{m}$	4 mm	$200\text{-}450 \mu\text{m}$
occupancy	$< 0.1 \%$	$2\text{-}10 \%$	$0.1\text{-}0.2 \%$

Table 2.3: Details of SDC tracking system.

concern was the high flux of photons in the tracking volume. These photons can interact with materials to create additional charged particles. This reduces the accuracy of energy measurement and particle identification in the calorimeters. Photon conversions also result in higher backgrounds within the tracking detectors. The need to minimize the amount of material available for photon conversions and multiple scattering within the ITD was one of the factors that made plastic MSGCs very attractive.

Figure 2.6: SDC tracking system.

The ITD was to consist of three superlayers (sets of detection planes) located at both ends of the silicon and barrel trackers. Each ITD detection plane was made from a number of MSGC tiles arranged on carbon fibre support wheels as shown in Figure 2.7. The average size of the MSGC tiles was 15 cm $\times$ 20 cm and the total area to be covered was 93 m².

Figure 2.7: ITD detector showing MSGC tiles in superlayer wheels.

At the $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ SSC design luminosity, and with the 63.5 MHz beam-crossing frequency there were expected to be some 10^8 proton-proton interactions per second. The MSGCs in the ITD had to be readout within 16 ns in order to identify the beam crossing in which the event producing the particles had occurred.

Figure 2.8: Simulated particle tracks for Higgs production and decay.

Figure 2.8 shows the numerous particles produced for a simulated interaction where a Higgs particle has been produced. It demonstrates the challenging task faced by the tracking detectors. The ITD MSGCs were located between 35 cm and 150 cm from the beam axis. The average charged particle flux in these regions was

calculated [25] [26] to range from $10^4 \text{ mm}^{-2}\text{s}^{-1}$ and $10^2 \text{ mm}^{-2}\text{s}^{-1}$. This rate did not include the effects of looping tracks within the magnetic field and converted photons. These increase the maximum flux incident on the MSGCs by a factor of four. The requirement imposed on the ITD MSGCs was that they have constant performance at all fluxes up to and including $10^5 \text{ mm}^{-2}\text{s}^{-1}$. This was an order of magnitude higher than the flux capability possible using the best MWPC technology.

2.2.2 ATLAS

ATLAS is one of two detectors which will be used to study proton-proton interactions at the Large Hadron Collider at CERN. It is larger, but lighter, than the other general-purpose LHC detector, CMS, and both detectors will likely make use of gas microstrip detectors. Table 2.4 provides a comparison of the two LHC detectors. The size and weight differences are due to the fact that ATLAS uses air-core muon toroids. The detailed design of the inner tracking at ATLAS is ongoing,

	ATLAS	CMS
length (m)	26	21.6
diameter (m)	22	14.6
weight (tonnes)	7000	14500
magnetic field (T)	2	4

Table 2.4: Comparison of ATLAS and CMS detectors.

but as currently configured the following types of detectors are all going to be used; MSGCs, silicon microstrips, gallium arsenide microstrips, silicon pixels, and straw tubes. As such it represents another example of the application of MSGCs in conjunction with other charged-particle detectors.

The ATLAS detector, shown in Figure 2.9, has an overall length of 26 m and a diameter of 22 m. The magnetic fields required for momentum determination are produced by 8-coil superconducting air-core toroids in addition to an inner solenoidal magnet.

Figure 2.9: ATLAS detector.

Inner tracking at ATLAS must provide precise momentum measurement of all charged particles with $p_T > 5$ GeV/c passing through the tracking volume, and also identify electrons. Like the SDC the pseudorapidity coverage of the ATLAS tracking system is $|\eta| < 2.5$. The inner tracking detector is contained within the 2-Tesla solenoid, which has a length of 6.8 m and a radius of 1.2 m. Figure 2.10

	Si	Si pixel	GaAs	MSGC	straw
rapidity	$ \eta < 1.4$	$ \eta < 2.5$	$2 < \eta < 2.5$	$1.4 < \eta < 2.5$	$ \eta < 2.5$
channels	$2.9(10^6)$	$1.4(10^8)$	$8(10^5)$	$1.5(10^6)$	$4.2(10^5)$
active region	41 m^2	2.2 m^2	3.3 m^2	51 m^2	12 m^3
spacing	$113 \mu\text{m}$	$50 \times 300 \mu\text{m}$	$50 \mu\text{m}$	$200 \mu\text{m}$	4 mm
element size	10 mm^2	0.015 mm^2	5 mm^2	30 mm^2	5000 mm^2
occupancy	$< 1 \%$	$< 0.01 \%$	$< 1 \%$	$< 2 \%$	100%

Table 2.5: Details of ATLAS tracking system.

shows this layout [27] of the ATLAS inner tracking system. There are twelve small MSGC wheels and one large MSGC wheel located on either side of the interaction point.

Figure 2.10: ATLAS inner tracking system.

There are three detection planes in each of the MSGC wheels. The size of each MSGC module (tile), illustrated in Figure 2.11a, is 13 cm $\times$ 16 cm, and the tiles are mounted on wheel supports as shown in Figure 2.11b. The flux 50 cm from the beam axis at the LHC is about $10^4 \text{ mm}^{-2}\text{s}^{-1}$ [28].

Figure 2.11: ATLAS MSGC (a) module (tile) (b) support structure (wheel).

Table 2.5 gives the various sub-systems which comprise the ATLAS tracking system, and provides details of each type of technology used. The size of each detector element is correlated to the occupancy which is one factor in choosing MSGCs in the locations specified over another type of detector.

2.2.3 Mammography

MSGC development has concentrated on the requirements of high-energy physics but there are other fields which have needs met by MSGCs. Among these other applications is that of medical physics imaging. MWPCs have been demonstrated in digital whole-body imaging, but these detectors lack the rate capability and resolution required for other types of medical imaging such as mammography.

Mammography uses relatively low energy (20 keV) photons which can be efficiently absorbed in a cm of high-pressure MSGC gas. By contrast 60 keV X-rays, typical of whole-body imaging, have an absorption length of 10 cm in atmospheric pressure xenon [4]. The spatial resolution possible with a 200 μm pitch MSGC system is better than that of X-ray film. The high quantum efficiency of the MSGC can reduce the total radiation dose to the patient compared to film methods. If routine and repeated screening continues to be a tool in the fight against breast cancer then reduction in accumulated dose is important. The digital images obtained using a MSGC system will permit image-processing and enhancement. The contrast of the image can be altered without having to expose the patient to a second X-ray as would be required with film. The mapping of the gray-scale in a digital image can be changed in order to accentuate features of interest.

In one approach to MSGC mammographic imaging a two dimensional image is obtained by scanning a slit along the anodes during the exposure. This requires that the MSGC be capable of operating at an instantaneous rate of 10^6 photons $\text{mm}^{-2}\text{s}^{-1}$, which is greater than any of the high-energy physics fluxes discussed earlier in this chapter. MSGCs with the appropriate surface resistivity have, as illustrated in Chapter 5, constant gain up to these rates using atmospheric pressure argon-based gas mixtures. With high-pressure, xenon-based, gas mixes the rate capability has yet to be demonstrated. Such mixes have reduced electron drift velocities and ion mobilities which will likely be the limiting factors rather than any surface-charging phenomena.

The choice of MSGC substrates used in mammography is less restricted com-

pared to those for high-energy physics applications. For a scanned system there is no limitation on the thickness of the substrate, and only the desire to have parallax-free devices requires a curved, plastic MSGC. However for an alternative scheme, where a segmented backplane of the MSGC is used to obtain 2-D information, very thin substrates are required.

The use of MSGCs in medical-imaging environments is now being pursued by the Carleton-CRPP group. Other than the requirement that the flux capability be as high as possible, and that the MSGC pitch be about $200\text{ }\mu\text{m}$, all other parameters will depend on the final system layout.

Chapter 3

Theory

This chapter presents a description of the MSGC geometry and discusses some of the important theory needed to understand how a MSGC works. The interactions between incident particles and the MSGC gas are discussed. In addition some of the theoretical foundation for the computer simulations is given.

Much of the theory presented here is common to other types of gas detectors. Radiation, in the form of X-rays or charged particles, ionizes some of the gas molecules. A discussion of the sources of ionizing radiation used in the testing of the MSGCs is presented in section 3.2. The type of radiation has a significant impact on the signals obtained in the detector. Charged particles leave a trail of ionization, while X-rays deposit all their energy in a localized region. Sections 3.3 and 3.4 will discuss these processes in greater detail. The electrons and ions created in the ionization move in the electric field of the detector. The specifics of the electron motion are important in determining the time structure of the detector signal, and the theory describing this motion is given in section 3.8. When the electrons get close to the anodes they gain enough kinetic energy in the high fields that they can create further ionization, and an avalanche is created which produces the signals. The avalanche process is discussed in section 3.5, and the formation of the actual signals on the MSGC electrodes is described in section 3.9.

3.1 MSGC Structure

Figure 3.1: MSGC cross-section.

Figure 3.1 shows a cross-section through a gas microstrip detector. The gas volume is enclosed by a drift plane and an anode-cathode plane which consists of alternating anodes and cathodes. High voltages are applied to the MSGC electrodes so that the anodes are positive with respect to the cathodes which are in turn positive with respect to the drift plane. An electric field is created between the anode-cathode plane and the drift plane such that any electrons within the gas volume will be attracted to the anodes of the MSGC. The distance between the drift plane and the anode-cathode plane, d , is known as the drift gap. The center-to-center distance between two anodes is the pitch of the MSGC. The width of the anode is w_{anode} , the width of the cathode is w_{cath} , and the length of the substrate surface between an anode and a cathode is w_{subs} .

$$\text{Pitch} = 2w_{subs} + w_{anode} + w_{cath}.$$

A backplane on the rear surface of the substrate can be used to shape the electric fields in the gas and reduce surface charging as discussed in the next section. When thin plastics are used the signals on the backplane are sufficiently large such that they can provide a convenient means of obtaining two-dimensional readout. For most of the gas volume, except between the anode-cathode plane and a height roughly equal to the MSGC pitch, the electric field is constant and is known as the drift field. The drift field, E_{drift} , is an important MSGC parameter since, as described in section 3.8 and Chapter 7, the electron velocity and diffusion in this drift region are critical in determining MSGC performance.

Unlike the high-field regions just above the anode-cathode plane, where sophisticated electrostatic modelling is required, the value of the drift field can be determined [23] [29] using a simple relationship,

$$E_{drift} = \frac{V_{drift} - V_{mean}}{d} \quad (3.1)$$

where the mean voltage of the anode-cathode plane is

$$V_{mean} = \frac{V_{anode}w_{anode} + V_{cath}w_{cath} + (V_{anode} + V_{cath})w_{subs}}{pitch} \quad (3.2)$$

Using these expressions the 400 μm pitch plastic MSGCs had a drift field of 4 kV/cm. This agrees with the results of detailed electrostatic modelling of the entire gas volume.

3.1.1 Substrate Resistivity and Charging

The resistivity of the substrate surface is critical in determining how a MSGC will work. If inappropriate substrates or operating voltages are used then a MSGC will be subject to a process known as “charging”. This has been one of the most studied aspects of MSGC theory [23] [30] [31] [32].

Charging is a dynamic process responsible for time and flux dependent changes in the gas gain of a MSGC. This variation must be minimized, and ideally the

MSGC performance remains constant in time no matter how the flux of incident ionizing radiation changes. Charging is due to the accumulation of charges, both ions and electrons, at the substrate surface. These charges are produced in the gas avalanches, and their effect is to modify the electric field in the MSGC and change the gas gain. In most situations the result is dominated by the positive ions which have the effect of reducing the gas gain. Eventually an equilibrium is reached where the rate of accumulation of surface charge equals the rate at which this charge is removed.

There are two ways to reduce charging. The first and most fundamental way is to use a substrate with a low surface resistivity. This motivated the use of materials such as ion-implanted plastics, special conductive glasses, and thin-film coatings. The lower the surface resistivity the higher the fluxes at which the gas gain remains stable. However a very low resistivity can result in large currents which increase the noise when the MSGCs are read-out with fast electronics. The second way is to use voltages which minimize the electric field crossing the substrate surface between the anodes and cathodes. This is a compromise since the most stable voltage configuration does not correspond to the highest possible gas gain [23]. To achieve the most stable gain the backplane voltage should equal the anode voltage however higher gain is obtained when the backplane voltage is equal to the cathode voltage.

3.2 Sources of Ionizing Radiation

3.2.1 Radioactive Sources

⁵⁵Fe Sources

⁵⁵Fe produces X-rays by electron capture.

and has a half-life of 2.73 years. It is manufactured by the neutron bombardment of ^{54}Fe , via the reaction $^{54}\text{Fe}[n, \gamma]^{55}\text{Fe}$ and is supplied in the form of a liquid solution. Sources of the desired activity were obtained by evaporating this liquid in a source holder. The ^{55}Fe sources used in the MSGC testing were made at the National Research Council (NRC) by Gary Bowes.

Electron capture is the process where an electron from one of the inner orbits, usually the K-shell, is captured by the nucleus. A proton is transformed into a neutron with the subsequent emission of a neutrino. X-rays are produced when additional electrons fill the orbital vacancies left by the captured electrons. In the case of ^{55}Fe the X-rays are those characteristic of ^{55}Mn which is the decay product. Table 3.1 gives the X-ray energies and transition probabilities for the three principle transitions. Note that a ^{55}Fe 5.9 keV X-ray corresponds to a wavelength of 0.210 nm. The interactions between ^{55}Fe and argon [33] [34] were of particular

Transition	Probability	Energy (keV)
$K\alpha_1$	58.5 %	5.899
$K\alpha_2$	29.6 %	5.888
$K\beta$	11.9 %	6.490

Table 3.1: ^{55}Fe transition energies.

importance during the MSGC testing. For 88% of the events two electrons are produced, namely the primary photoelectron with an energy of $(5.9 - \mathcal{E}_i)$ and an Auger electron of energy $\mathcal{E}_i$ equal to the electron energy levels of argon (Table 3.2). These electrons typically have a range of about 150 μm at atmospheric pressure. In the remaining 12% of the events a fluorescence X-ray is emitted instead of the Auger electron. This fluorescence X-ray, emitted via K-shell to L-shell transitions, has a high probability of escaping from the active gas volume so that only the energy of the primary photoelectron is detected. This is the basis for the 3 keV escape peak seen in argon-based gas mixtures, and which will be illustrated in Chapter 5. The range of 5.9 keV X-rays in atmospheric pressure argon is 3 cm, which corresponds to a photon mass attenuation length of 0.3 cm^{-1} .

Shell	Energy $\mathcal{E}_i$ (keV)
K	3.206
L ₁	0.326
L ₂	0.251
L ₃	0.249
M ₁	0.0292
M ₂	0.0159
M ₃	0.0157

Table 3.2: Electron shell energies of argon.

^{55}Fe sources are "open" sources because the 5.9 keV X-rays are not very penetrating, and therefore these sources required careful handling to minimize the possibility of ingestion or inhalation. The license-exempt level of activity is 100 μCi and the ^{55}Fe sources used in the MSGC testing were at or below this level.

^{90}Sr Sources

^{90}Sr is a β^- emitter which has a half-life of 28.8 years. The maximum kinetic energy of the emitted electron is 546 keV and ^{90}Sr is one of the best high-energy long-lived β^- sources. Because there is no defined structure in the spectrum this source served mainly just as a quick means of determining if a MSGC was "working" in any sense. The ^{90}Sr sources used during the testing were "closed" sources with activities also of about 100 μCi .

3.2.2 X-ray Generator

X-ray generators are alternatives to the intense radioactive sources which would have to be used in order to study the high-rate behaviour of MSGCs in the laboratory. Such studies must be carried out at fluxes of up to 10^7 photons $\text{mm}^{-2}\text{s}^{-1}$. X-ray generators are more convenient to use because the rate can be varied without significant changes to the geometry. An Oxford Instruments, copper-targeted, X-ray tube was used for the plastic MSGC testing which was ca-

pable of 30 kV operation with a maximum current of 2 mA. The X-ray spectrum had a peak at the 8 keV copper K_{α} energy as well as a continuum extending all the way up to the primary electron voltage. An 8 keV photoelectron has a range of 160 μm [9] in an atmospheric pressure 90-10 argon-DME mix.

3.2.3 Particle Accelerators

The only practical way to obtain a beam of high-flux, high-energy charged particles is from large accelerators designed for this purpose. These particle accelerators have many different designs, but all use a few basic principles. If a particle is charged it can be accelerated by applying an electric field. In an accelerator, such as a cyclotron or synchrotron, this is done using radio-frequency cavities and circulating beams. The timing is carefully adjusted so that each time a bunch of particles enters an accelerating cavity the phase of the electric field is such that the particles are subjected to an accelerating force. The particle bunches are maintained in their orbits using strong magnets to bend and focus them. The energies of the particles can be increased anywhere from tens of MeV to a TeV, depending on the particular machine size and design. As mentioned previously the LHC will have a beam energy of 7 TeV.

The plastic MSGCs were tested at three different accelerators, two of which were located at CERN and the third at TRIUMF. The CERN accelerators were the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS). At TRIUMF the accelerator was the main cyclotron. In all cases the MSGCs were installed in secondary beams, created when the primary beams interacted with targets producing secondary particles whose momenta were selected using magnetic elements.

3.3 Minimum-Ionizing Particle Interactions

Consider a singly-charged high-energy particle which is travelling through a target material. The average energy loss per unit length due to interactions which

result in excitation or ionization is given by the Bethe-Bloch relation,

$$\frac{\Delta E}{\Delta x} = \frac{2.549(10^{-25})}{\beta^2} n_e \left[2 \ln \left(\frac{2m_e c^2 \beta^2}{I(1 - \beta^2)} \right) - 2\beta^2 - \delta(\beta) \right] \quad (3.4)$$

where n_e is the electron number density of the target material, m_e is the electron rest mass, I is the mean excitation energy, and the particle is travelling at a velocity β with respect to the speed of light. The energy loss for a heavy charged particle in atmospheric-pressure argon is given by

$$\frac{\Delta E}{\Delta x} = \frac{0.1224}{\beta^2} \left[2 \ln(5436) + 4 \ln \beta - 2 \ln(1 - \beta^2) - 2\beta^2 - \delta(\beta) \right] \quad (3.5)$$

while for an electron the energy loss is

$$\frac{\Delta E}{\Delta x} = \frac{0.1224}{\beta^2} \left[2 \ln(5436) + 4 \ln \beta - 1.5 \ln(1 - \beta^2) - 1.95\beta^2 - \delta(\beta) \right]. \quad (3.6)$$

For high-energy electrons, above tens of MeV, the dominant energy loss mechanism is not ionization, as described by this expression, but rather bremsstrahlung ("stopping" radiation) where the electrons radiate electromagnetically as they are accelerated in the target material.

Figure 3.2: Energy loss for electrons, pions, and muons in argon gas.

The average Bethe-Bloch ionization energy loss per unit length is plotted as a function of the particle's momentum in Figure 3.2. For each type of particle the average energy loss falls to a minimum value followed by the "relativistic rise" which eventually saturates due to density effects. These effects are taken into account via the $\delta(\beta)$ term. The momentum at which the minimum average energy loss occurs depends on the particle type however the minimum energy loss is essentially the same for all particles. A minimum-ionizing particle, MIP, is therefore a convenient standard for measuring the performance of any detector. Actual charged particles will deposit an average energy equal to, or greater than, that of a MIP so this represents a worst-case scenario. For most materials, including detector gases, the average energy deposited by a minimum-ionizing particle is $2 \text{ MeV g}^{-1}\text{cm}^2$ and so typically the average energy deposition per unit length, $\Delta E/\Delta x$, in a gas is 0.2 keV mm^{-1} .

In gas detectors, such as a MSGC, the total energy loss is described by the Landau distribution shown in Figure 3.3. This energy loss distribution is evidenced in the statistics of the ionization, namely in how many electron-ion pairs are created by the passage of the ionizing particle.

Figure 3.3: Energy deposited in argon by a MIP.

For MIP interactions there are two important quantities describing this process which are specific to the particular gas mix. The first, n_p , is the average number of primary electron-ion pairs created per unit length. The actual number produced by a MIP is governed by Poisson statistics, and represents the number of discrete points along the particle track where electron-ion pairs are formed. At each interaction point the primary electrons may have sufficient energy to produce further ionization resulting in a cluster of electrons and ions. The second number, n_t , is the average number of total electron-ion pairs created per unit length and reflects the size of the ionization clusters. If the average ionization energy is W_i then

$$n_t = \frac{(\Delta E / \Delta x)}{W_i}. \quad (3.7)$$

The cluster size distribution can be experimentally determined or predicted using models such as the Electrons Locally Deposited (ELD) model [35]. Most clusters consist of only a few electrons, with single-electron clusters dominating as shown in Figure 3.4. This gives the cluster-size distribution for a 90-10 argon-isobutane gas mix. This gas mix was used in the laboratory, at beam tests, and in the MSGC simulations.

Figure 3.4: Cluster-size distribution in 90-10 argon-isobutane gas.

Table 3.3 gives the properties for some of the constituent gases commonly used in MSGCs. All the values are for atmospheric pressure and room temperature (20°C). The table was compiled using a number of sources [33] [36] [37] [17] [38] and whenever conflicts existed between the values from two or more sources the most recent experimental results were often favored over the older data. This is not unreasonable since improvements, especially in terms of electronics and gas purity have made some of the newer results more reliable. The choice of gas for

Gas	W_i (eV)	$\Delta E/\Delta x$ (keV/mm)	n_p (mm ⁻¹)	n_t (mm ⁻¹)
Ar	26.4	0.244	2.9	9.5
CH ₄	28.3	0.148	2.5	5.6
iso C ₄ H ₁₀	23.2	0.450	8.4	19.5
CF ₄	54	0.281	4.1	5.3
Xe	22	0.676	4.4	30.7
He	41	0.032	0.42	0.78
DME	28	0.422	6.2	15.0

Table 3.3: Properties of gases used in MSGCs.

a MSGC is one of the most important of the factors which determine how it will perform. In general one wants a gas which has large primary ionization, high gas gain, large drift velocity, small electron attachment, and good ageing properties. However other criteria such as cost, safety, and environmental considerations may have priority. Xenon is a very good gas in terms of having large ionization but it is also extremely costly. This prohibits its use in most large scale HEP applications however it will be required in MSGC medical imaging. Argon is the least expensive of the noble gases and, not surprisingly, is one of the most commonly-used gases in both MWPCs and MSGCs. Other gases such as CF₄ (carbon tetrafluoride) [39], which is an extremely fast gas, have purity requirements that necessitate filtering and raise issues of long-term reliable supply. CF₄ mixes often suffer from large electron attachment [21] which degrades MSGC energy resolution and efficiency. Another important consideration is the effect of the gas on the materials from

which the detector is constructed, including the MSGC substrate and the chamber components. CF_4 and dimethylether (DME) react with some materials including fibreglass and Tedlar.

3.4 X-ray Interactions

X-rays, such as those produced by ^{55}Fe or an X-ray generator, interact with the gas in a MSGC quite differently than do minimum-ionizing particles. The interaction produces a fairly-localized electron cloud initiated by a primary electron which is created upon absorption of the X-ray photon. This photo-electron is preferentially emitted perpendicular to the X-ray track. The extent of the electron cloud is an important factor, especially in medical applications where the goal is to image X-rays using MSGCs at high resolution. The high drift field in a typical MSGC reduces the radial size of the electron cloud and increases its longitudinal extent. The number of electrons in the X-ray induced cloud is the X-ray energy divided by the average ionization energy of the detector gas.

3.5 Gas Amplification

Gas microstrip detectors depend on the avalanche process which occurs in the high-field regions near the anodes. The motion of the electrons and ions created in these avalanches create signals which are large enough to be detected with subsequent electronic amplifiers. Typically avalanche amplification starts at field strengths of about 10 kV/cm, which are usually only found at distances of the order of 100 μm away from the anodes in a MSGC. For example, with a glass MSGC [8], and a 95-5 argon-DME gas mix, there is gas amplification in the drift region when the drift field is $E_{\text{drift}} = 6 \text{ kV/cm}$. Simulations, described in Chapter 7, determined that in a 90-10 argon-isobutane gas mix amplification is significant only when the field exceeds 7 kV/cm. Many MSGCs are operated with gain in the drift region, but all the plastic MSGCs had drift fields below the threshold for

multiplication.

The first Townsend coefficient, α , is the parameter which describes the multiplication process in a gas avalanche. The increase in the number of electrons after a distance Δx has been travelled is given by $e^{\alpha \Delta x}$. The Townsend coefficient is the inverse of the mean free path for ionization and represents the number of ionizing collisions per unit distance. Any attempt at understanding or simulating the gas gain in a MSGC requires an estimate of the value of α for the particular gas mix being used, and this is complicated by the fact that it is an E-field dependent quantity. Data are sparse or completely non-existent for α at high fields (several tens of kV/cm to MV/cm) especially for many of the MSGC gas mixes used in this research. It is then necessary to rely on parameterization of the few experimental data sets [40] [41] [42] [43] and on numerical simulations. Typically the Townsend coefficient is characterized at low and moderate electric fields as

$$\frac{\alpha}{p} = f\left(\frac{E}{p}\right) \quad (3.8)$$

where p is the pressure of the gas, E is the electric field strength, and f is some function to which the experimental data are fitted. There are a multitude of different parameterizations [41] [44] and which one best fits the data depends on the values of E/p .

The distribution of the total number of electrons, N , in a gas avalanche initiated by a single electron is described by the Polya distribution [45] [21] [35]

$$P(N) \propto \left(\frac{bN}{\bar{N}}\right)^{b-1} e^{-\frac{bN}{\bar{N}}} \quad (3.9)$$

where $\bar{N}$ is the mean number of avalanche electrons and b is a measure of the gas gain fluctuation.

$$\frac{1}{b} = \left(\frac{\sigma_N}{\bar{N}}\right)^2 \quad (3.10)$$

3.6 Ageing

Ageing is a process where materials from the gas are deposited on the MSGC electrodes, principally on the anodes, resulting in a reduction in the size of the signals. This process is well-known in wire chambers, but the effects in MSGCs are expected to be more serious. The presence of the MSGC substrate introduces additional surfaces that may contribute to the amount of material which can be deposited, and the surfaces themselves may be affected over time. This is of most concern when thin layers have been used to alter the surface resistivity or to aid in passivation. The electric fields in a MSGC are higher than those in a MWPC, and in particular the high anode surface fields are expected to lead to more significant gas polymerization and deposition.

CF₄-isobutane mixes are attractive because they have been found to etch these deposits in MWPCs. Organic gases themselves, such as methane, ethane, and isobutane have demonstrated very poor ageing properties when combined with noble gases [46]. Argon-DME is hoped to provide adequate ageing for ATLAS and effort is ongoing to study its ageing properties [47]. MSGCs fabricated on electronically conducting glass substrates with gold electrodes have shown stable gains up to accumulated charge of 130 mC/cm with a 90-10 argon-DME gas mix in a clean stainless-steel gas system [48]. Ageing is often dominated by contaminants in the gas which originate from the supplier or from outgassing of materials used in the construction of the MSGC chambers. This is why ageing results often vary significantly from one system to another.

3.7 Gas Mixtures

The vast majority of the characterization of plastic MSGCs reported here has been performed using gas mixes where argon was the main constituent gas. It is important to understand the properties of these argon-based gas mixtures both in terms of use in the simulations and for understanding the experimental results. Argon is a noble gas whose energy levels, $\mathcal{E}_i$, were listed in Table 3.2. Like all

other noble gases argon is a monatomic inert gas which is easily ionized, and which has filled spherical electron shells. The only way an argon ion can release energy is via ionization or excitation. The effective ionization potential is close to the M-shell ionization. For argon the first ionization energy is 15.76 eV and the excitation potential is 11.6 eV.

Argon-based gas mixtures, where organic gases are used as quenchers, typically have electron drift velocities of between 30 and 50 $\mu\text{m}/\text{ns}$ at an electric field of 4 kV/cm. There are about 10 electron-ion pairs deposited per mm of interaction length for minimum-ionizing particles, and MSGC gas gains are normally 2000. With only one exception all the results presented in this thesis, and given in Chapters 5, 6, and 7, were for MSGCs operated with argon mixed with either methane, isobutane, or DME. The only non-argon mix used was CF_4 -isobutane, which has the potential for good ageing properties and has significantly higher electron drift velocity (120 $\mu\text{m}/\text{ns}$).

Isobutane is a common quench gas which has an effective ionization potential close to that of argon. A quench gas has good photon absorption to prevent secondary ionization and organic gases, such as isobutane, have many vibrational and rotational modes which effectively absorb energy. DME, which will be mixed with argon in a 50:50 ratio for the MSGCs at ATLAS, has a first ionization potential of 10 eV.

The drift velocity and other parameters of a gas mix are sensitive to the exact gas ratio, pressure, temperature, and contaminants. For example water vapour has been found to have significant effects in argon-methane mixes at concentrations of as little as a few tens of parts per million [49]. Such effects are most pronounced at relatively low electric fields typical in some MWPCs, however they will also be present to a lesser extent in the high fields of MSGCs. Other common contaminants such as oxygen can also dramatically affect the ageing process. However during the plastic MSGC research such effects were neglected since the motivation was primarily to gain a better understanding of the fundamental detector operation.

Both in the laboratory and at test beams the composition of the MSGC gases was known only to an accuracy of a few percent. The purity and the exact identity and quantification of any contaminants were unknown in most cases.

3.8 Electron Drift in Gases

The details of electron drift are very important in terms of determining how a MSGC will perform. The electron drift velocity and the electron diffusion, both longitudinal and transverse, are among the most critical parameters in any attempt to model MSGC operation.

The motion of electrons in a gas, including in the presence of an electric or magnetic field, is described by the Maxwell-Boltzmann transport equation [50] as given below,

$$\frac{\delta f}{\delta t} + \vec{v} \cdot \nabla_{\vec{r}}(f) + \vec{a} \cdot \nabla_{\vec{v}}(f) = Q_{\sigma} \quad (3.11)$$

where the electron velocity distribution, $f(\vec{r}, \vec{v}, t)$, is a function of position, $\vec{r}$, velocity, $\vec{v}$, and time, t . Q_{σ} is the change in the distribution due to electron scattering. The acceleration, $\vec{a}$, for an electron with charge, e , and mass, m , in a constant electric field, $\vec{E}$, is equal to $(e\vec{E})/m$. The transport equation represents the continuity equation in six-dimensional position-velocity phase space. The population of electrons in an element of this phase space changes with time due to their velocity, acceleration, and collisions.

If the electron velocity distribution is known then the electron drift velocity in a given direction, say along the x -axis, can be calculated

$$v_{drift} = \langle v_x \rangle = \int \int v_x f(\vec{r}, \vec{v}, t) d\vec{v} d\vec{r} \quad (3.12)$$

and the diffusion constant is

$$D_x = \frac{1}{2} \langle v_x^2 \rangle \frac{d \langle x^2 \rangle}{dx} \quad (3.13)$$

The Maxwell-Boltzmann equation has been solved numerically [51] using a multiterm expansion (via Legendre polynomials) in the program MAGBOLTZ which will be further discussed in Chapter 7. The electron drift velocity and electron diffusion coefficients were obtained for all the gas mixes subsequently used in the MSGC simulations.

3.9 Induced Signals on the MSGC Electrodes

An important aspect of MSGC operation is the production of the actual signals induced on the electrodes. This theory is especially useful when it comes to the problem of MSGC simulation where the signals are subsequently shaped by fast read-out electronics to permit numerical comparison to experimental results.

The method used by gas microstrip simulations to produce the signals on the MSGC electrodes is based on Ramo's theorem [52] which was used over fifty years ago to aid in the design of vacuum tubes [53] [54] [55]. This useful theorem states that the instantaneous current induced on any given electrode due to the motion of a singly-charged particle is

$$i = evW_v \quad (3.14)$$

where e is the electron charge and v is the instantaneous particle velocity. W_v , the weighting field, is the normalized component of the electric field in the direction of the velocity obtained when the electrode in question is at unit potential while all other conductors are grounded. Equation 3.14 holds for both electrons and ions, but the contribution from the motion of the ions in gas detectors (including MSGCs) is greater than the electron component.

Ramo's theorem was derived using Gauss's law and Green's theorem, and it has proved useful in the analysis of the signals in semiconductor detectors [56] [57]. It is an alternative approach to considering an energy balance, such as commonly done in the case of a simple single-wire proportional tube however it leads to the same final result. Namely that the current signal on the anode wire of a cylindrical

prop tube is

$$i(t) = \frac{\kappa}{t + t_o} \quad (3.15)$$

where κ and t_o are constants depending on the proportional tube geometry and operating voltage. Figure 3.5 shows a typical proportional-tube current signal.

Figure 3.5: Current signal in proportional tube.

Chapter 4

MSGC Prints

The production of MSGCs on plastic substrates has required extensive collaboration with industry. Unlike silicon or glass substrates the microelectronics industry had little experience in producing high-quality prints on plastics. Although the MSGC structures, with the smallest feature being the 10 μm wide anodes of a 200 μm pitch pattern, are easily within the resolution of standard ultraviolet (UV) photolithography, the defect density requirements are significantly different from integrated circuit (IC) production.

In conventional production several hundred ICs are produced per wafer. Even with a yield of only 20% the number of useful devices from a given wafer is substantial. Defect density is fixed by the process steps and it is more difficult to maintain yield as the size of the IC increases. In the case of a MSGC print it only takes a few major defects within the active area to render the detector unusable. A MSGC can be thought of as a giant, single-layer, large linewidth IC when it comes to production issues. Each MSGC print must have quality equivalent to a defect-free mask, which is a standard, yet non-trivial, task even with respect to the glass substrates commonly used in the industry. The introduction of plastic materials complicated the problem.

4.1 Production

The two main suppliers of the plastic MSGC prints were Precision Photo Mask (PPM) of Montreal, Quebec, and Spire of Boston, Massachusetts. PPM produced all the masks, described in section 4.1.6, from which these prints were made. Among the other institutions who, at one time or another, fabricated MSGC prints for the Carleton-CRPP group were Merrimac Industries, Filtran, and the National Research Council (NRC), all of Ottawa, Ontario. Etalon and HTA, in the U.S., were involved in the MSGC fabrication.

Aluminum and gold MSGC prints on Tedlar and Upilex were made using wet etching at PPM. Gold on Upilex prints were made using liftoff at Spire. High-quality gold on ion-implanted Upilex prints were obtained by both wet-etch and lift-off processing. The low deformation temperatures of plastics required that new processes be developed. It was necessary to combine good edge quality, electrode-width uniformity, and adhesion with low defect density and the correct resistivity substrate. Edge quality and electrode-width uniformity were the most easily achieved, while adhesion and low defect density were the hardest to obtain.

4.1.1 Substrates

The choice of the substrate is one of the most important decisions to be made in producing gas microstrip detectors. Among the factors to be considered are, bulk and surface resistivity, surface quality, radiation length, radiation hardness, chemical stability, lack of out-gassing, suitability for photolithography, durability, availability, and cost. A wide range of substrates have been used to produce MSGCs. The field is dominated by MSGCs fabricated on various types of glasses. MSGCs have also been produced on silicon and printed circuit board material [58]. Plastics were chosen by the Carleton-CRPP group for use in the SDC [24] discussed in Chapter 2. The minimization of radiation length, and consequently photon conversions and multiple scattering, was an important requirement favoring plastic MSGCs. The next section provides additional factors which made plastic

MSGCs so attractive, and gives detailed information on the two plastics used to build the Carleton-CRPP MSGCs.

Surface Resistivity

As described in the previous chapter the surface of a MSGC substrate must provide suitable conduction to dissipate any charges which may be present on the surface between the anodes and cathodes. These surface charges, which originate in the MSGC avalanches, distort the electric fields and are responsible for rate-dependent performance.

Surface resistivity is quoted in terms of $\Omega/\square$. As illustrated in Figure 4.1 this is a convenient way of determining the resistance between two structures on a thin film of thickness, t , whose bulk resistivity is ρ . It can be used to quantify surface resistances without having to know the actual details of the substrate, such as the depth of an ion-implanted conduction layer.

Figure 4.1: Definition of surface resistivity. In this example there are two squares ($\square$ s) between the electrodes.

If the surface resistivity is greater than $10^{16} \Omega/\square$ MSGCs will show rate dependence. The resistance cannot be too low since this results in unacceptable levels of power dissipation. In addition large DC currents, and the corresponding shot noise, make read-out difficult with fast electronics. For instance in the LHC environment shot noise must be limited to less than a few mV, and this puts an upper limit of about one μA on the current per anode. With a typical $200 \mu\text{m}$ pitch

geometry this corresponds to a surface resistivity of $10^{12} \Omega/\square$, and this represents the lower end of the resistivity range. MSGCs with resistivities in the range from $10^{12} - 10^{16} \Omega/\square$ are suitable for high-rate, low-noise operation. A surface resistivity of $10^{14} \Omega/\square$ was the target value for ATLAS and CMS applications.

The required surface resistivity can be obtained in different ways. One can select a substrate whose inherent bulk resistivity yields the correct surface value. Unfortunately very few materials, and certainly none of the common ones, have bulk resistivities which give the desired surface resistivity. Most plastics, such as polyethylene, Mylar, Teflon, and Kapton, have resistivities which are too high. Similarly most glasses, ceramics, and other insulators like fibreglass are too resistive. Some materials, such as intrinsic semiconductors, are too conductive. The problem of finding a material with the correct bulk resistivity is made more difficult when combined with the need for a high dielectric strength, chemical inertness, radiation hardness, and low cost.

Alternatively the surface resistivity of the substrate can be modified. Resistivity modification of a MSGC substrate can be achieved via ion-implantation or thin-layer deposition with nickel-nickel oxide, silicon nitride, or lead silicate [59].

Plastics

Plastics are flexible, facilitating non-planar MSGC geometries [60], and potentially can be thinner than glasses [48] [61]. In addition to increasing the radiation length this enables backplane readout to obtain 2-D information. All the Carleton-CRPP MSGCs used either Tedlar or Upilex (Kapton) as the substrate material. Table 4.1 summarizes the characteristics of these two plastic materials.

Tedlar The first MSGCs tested locally were made on white Tedlar. This is a polyvinyl fluoride (PVF) manufactured by DuPont. Tedlar comes in many different forms, and is used in the aerospace industry and as mold-release agent. One interesting initial finding was that only the pigmented (white) Tedlar gave good working detectors while clear unpigmented Tedlar samples did not. The presence

	White Tedlar	Upilex (Kapton)
ρ (Ωcm)	10^{14}	10^{17}
theoretical R_s ($\Omega/\square$)	10^{16}	10^{19}
measured R_s ($\Omega/\square$)	5×10^{15}	5×10^{17}
ϵ_r	11.0	3.5
dielectric strength ($\text{V}/\mu\text{m}$)	80	200
thickness (μm)	97	125
radiation length (cm)	20.5	27.5

Table 4.1: Plastics used to fabricate the MSGCs.

of the white coloring agent, titanium oxide, reduced the resistivity of the material to a point low enough to negate charging. The surface resistivity of white Tedlar was at the high end of the usable range for MSGCs, which made it suitable for low to moderate flux operation. Clear Tedlar had a bulk resistivity of $10^{16} \Omega\text{cm}$, and a surface resistivity of $10^{18} \Omega/\square$ which was well outside of the suitable range.

The TiO_2 granules which corrected the resistivity also caused the surface to be rough, making the photolithography more difficult. The scanning-electron microscope images presented in Figure 4.2 show the Tedlar surface, which can be described as being white TiO_2 popcorn-like nodules embedded in a translucent PVF matrix. X-ray elemental analysis confirmed that the nodules were the titanium-containing constituents of the Tedlar.

Figure 4.2: SEM images of white Tedlar (a) 7000 X (b) 20000 X.

Tedlar, like other halogen-containing materials, was affected by exposure to DME which is a component of one of the most widely used MSGC gas mixes, namely

argon-DME. This was one factor which indicated that a more suitable plastic was required, particularly for high-energy physics applications.

Upilex (Kapton) Upilex is a polyimide distributed by ICI in the United States and made by UBE Industries in Japan. Kapton is the trade name for the same polyimide made by DuPont. Polyimide is short for poly[N,N'-(p,p'-oxydiphenylene)]pyromellitimide. The chemical formula is $(C_{22}H_{10}O_5N_2)_n$. Kapton was initially used for producing MSGC prints, but this material was replaced by high-quality, Type-S, Upilex from UBE. This Upilex had fewer pre-existing defects and better scratch resistance. There were two distinct surfaces on the Type-S Upilex. One surface was very smooth while the other contained microscopic pits visible under 40 X optical magnification. For the purposes of production of MSGCs the smooth surface was preferred for both the ion-implantation and subsequent lithography. All results presented in this thesis were for 125 μm thick Upilex, however some prints were produced on 50 μm material. Unlike Tedlar, both Kapton and Upilex were unaffected by exposure to DME or CF_4 gas and therefore suited for the ATLAS environment.

Glass and Other Substrates

Most MSGC research has been on detectors using glass substrates of one sort or another, where quartz is considered a glass for this categorization. Normal, semi-conducting, and ion-implanted glasses have been investigated. Table 4.2 gives the properties of four glass substrates. The dominance of glass in the MSGC community is reflected by the fact that there have been about 50 journal papers to date describing such devices, while less than 20 have been on plastic MSGCs (of which 7 have involved Carleton-CRPP research). This has primarily been due to the fabrication issues mentioned previously. Industry was familiar with producing high-quality large-area metallizations on glass substrates for use as IC masks. The transition from standard mask glasses to some of the more exotic MSGC glass substrates, such as the two electronic-conductivity glasses listed in the table, has

Glass Type	conduction mechanism	ρ (Ω .cm)	thickness (μ m)	radiation length (cm)
Pestov(Moscow)	electrons	$10^9 - 10^{12}$	500	4.4
Schott S-8900	electrons	$10^{11} - 10^{12}$	500	4.6
Desag D-263	ions	10^{15}	300	12.4
Hoya SL	ions	$> 10^{15}$	1000	13.0

Table 4.2: Characteristics of MSGC glasses.

been more straight forward than that from glasses to plastics.

There are two significant disadvantages of glass MSGCs compared to plastics. Because of handling difficulties and fragility the glass MSGC substrates cannot be thinner than about 300 μ m, and very large detectors must be even thicker. Secondly, as illustrated in the tables, the radiation length of glasses are shorter than those of plastics. This latter problem is of such concern in HEP applications that the Pestov and Schott S-8900 glasses could only be used as a thin coating on a thicker support made from a longer radiation length glass. In the case of large MSGCs, such as those for the SDC, the plastics were supported on a carbon-fibre/foam sandwich. An ITD MSGC tile was 0.088% of a radiation length, of which 0.036% was from the 100 μ m thick Upilex, and 0.052% was due to the support. In comparison a MSGC built on 300 μ m thick Desag (Deutsche Spezialglas AG) D-263 glass has a radiation length of 0.24%.

4.1.2 Ion-implantation

In the case of plastic substrates the term ion-implantation is somewhat misleading but, as is traditional within the MSGC community, this terminology will be used throughout this thesis. Unlike crystalline materials, such as silicon or quartz, there is in fact no implantation of the ions in plastics. Resistivity modification is not due to changes in lattice and electronic structure such as in conventional ion implantation. However, as with crystal substrates, the layer of greatest change in resistivity is below the actual surface, so in this sense the description of the process as implantation is appropriate. The change in surface resistivity of the plastic is

due instead to the breaking of the polymer chains and carbonization of the material at and just below the surface. The volatile nitrogen, oxygen, and hydrogen elements disassociate leaving behind a conductive amorphous carbon layer.

Preliminary investigations in the use of ion bombardment to alter the resistivity of Kapton were made in conjunction with Orenda, a division of Hawker Siddley, Canada. This firm had some expertise in the ion implantation of turbine blades for aircraft engines which increases their durability. Implantation of Kapton was done using both copper and carbon ions at a variety of doses (10^{13} to 10^{16} ions cm^{-2}) and ion energies (50 to 400 keV). Surface resistivities in the desired 10^{12} – 10^{15} $\Omega/\square$ range were obtained. As part of this effort important techniques for the measurement of surface resistance, substrate inspection and characterization, and substrate handling methods were developed.

In this early stage of the research the goal was the SDC and large areas of polyimide would have to be ion-implanted at the costs and time frames imposed by the project. A company, Spire, had experience and facilities for implanting large areas of light-weight plastic material, including Kapton. These modified-resistivity plastics are used in commercial and military satellites to reduce the build-up of static charges while in orbit. Spire had shown that it could modify the surface resistivity of Kapton by up to 14 orders of magnitude. Most of the polyimide material used to date had been implanted in a facility at Spire which allowed for the implantation of four 40 cm by 40 cm sheets at one time. All the ion-implanted Kapton and Upilex from Spire has been produced using bombardment with 80 keV argon ions at doses ranging from 10^{14} to 10^{16} ions/cm. The depth of the modified layer was determined at Spire to be at most 0.5 μm , and 0.25 μm was taken to be the nominal thickness for use in electrostatic simulations.

4.1.3 Oxide coatings

Another technique to obtain surface resistivities in the desired range has been to coat the plastic MSGCs after fabrication with a thin (a few tens of nm)

nickel-nickel oxide (Ni-NiO) or Inconel oxide layer. This method was investigated locally and results can be found in [62]. Other MSGCs have made use of the Ni-NiO coating [61] which was developed by Martin Salomon at TRIUMF [63]. In addition to reducing the surface resistivity a Ni-NiO coating serves to "passivate" the MSGC against breakdowns between the anodes and cathodes. Nickel oxide has a low secondary-electron emission coefficient and the Ni-NiO coating appears to effectively suppress ion-induced secondary electron emission from the cathodes. As discussed in a subsequent section this is a major MSGC breakdown mechanism.

4.1.4 Metals

Table 4.3 summarizes the metals used in fabricating MSGCs. For the plastic detectors both aluminum and gold have successfully been used as the primary electrode metal. The final column in the table gives the resistance for a nominal 5 cm long, 10 μm wide, and 0.3 μm thick anode. The electrical resistance of the

	ρ ($\mu\Omega\text{cm}$)	m.p. ($^{\circ}\text{C}$)	anode (Ω)
Al	2.7	654	450
Au	2.2	1063	370
Cr	12.9	1857	2150
Ti	42.0	1660	7014
Ni	6.8	1452	1136

Table 4.3: Metals used in fabrication of the plastic MSGCs.

anodes can have an important impact on MSGC performance, as will be discussed in Chapter 6. Mask III and IV prints (see section 4.1.6) incorporated test structures specifically for measuring the metal resistance.

Aluminum MSGC print manufacturers in general, and PPM in particular, found it difficult to combine both low aluminum resistance and good lithography quality in terms of defects. Evaporated aluminum was found to have the correct resistance however the prints suffered from many defects, particularly those of a serious nature namely large inter-electrode blobs. Sputtered aluminum had measured resistances

of up to ten times what would be expected, but the corresponding MSGC prints were of excellent quality with few if any defects.

Gold Gold is far more durable than aluminum and this has become the metal of choice in MSGCs. Other groups have found that the ageing of MSGCs is minimized when gold electrodes are used.

Chromium Chromium is the standard metal used in the production of the optical masks used in the photolithographic processes described in the next section. Because the microelectronics industry has significant experience fabricating high-quality chromium structures on glass, chromium-on-glass MSGCs are common. Chromium has also been used as the metallization on other MSGC substrates, including plastics. However there are two major drawbacks in using chromium as the primary MSGC electrode material. Firstly, the electrical resistivity of chromium is substantially greater than that of either aluminum or gold, which as mentioned previously can complicate read-out. Secondly, chromium has shown to lead to more rapid ageing of MSGC chambers.

Chromium is commonly used as an adhesion layer for other metals in MSGC prints. Many of the gold-on-Upilex MSGCs described in this thesis had a thin initial layer of chromium, followed by titanium, then by a much thicker layer of gold. After severe high-flux testing the chromium in several gold on ion-implanted Upilex MSGC prints was found to have formed nodules at the edges of the anodes (see Figure 4.3).

Figure 4.3: SEM images showing chromium blobs on Upilex MSGC.

The chromium adhesion layer for these prints was determined to be ten times thicker than the design value. Once the amount of chromium was reduced the nodules were not found to develop on any subsequent Au-Cr-Ti MSGC print.

Titanium Titanium is a frequently used adhesion metal when gold is the primary electrode metal [48]. Unlike chromium there have been no problems with the titanium used in the gold adhesion layers.

Nickel Nickel is used in adhesion and as one of the primary materials in the resistivity-modifying coatings for the unimplanted Upilex MSGCs.

4.1.5 Adhesion

The adhesion of metal to the plastics proved difficult, particularly in the case of the polyimide substrates. This is similar to the experience of other groups working with polyimides [64]. Adhesion was checked using the "Scotch-Tape" test in which a length of 3M Translucent Adhesive tape was applied to the metallization under test and slowly pulled off. In most cases this test was done in a region outside of the active MSGC area since the residue from the tape would contaminate the surface. If no metal was pulled off the substrate surface then the print was deemed to completely pass the test. Conversely the print failed if a significant amount of the metal was lifted off by the tape. Harsh though this "Scotch-Tape" test may seem, it is a standard technique in the photolithography industry, and eventually all the plastic MSGC prints achieved this level of adhesion.

As described previously when gold was used as the electrode metal an adhesion layer was always required for both Tedlar and Upilex substrates. This layer consisted of another metal or metals, with nickel, chromium, and titanium being used in various combinations. It was found that adhesion was substantially more difficult to achieve with ion-implanted polyimides than unimplanted polyimides. Aluminum generally had good adhesion to both Tedlar and Upilex without the need for an intermediate layer.

4.1.6 Lithography

The MSGC prints were produced using photolithographic processes which have been optimized to produce high-quality large-area prints on thin plastics. 86% of the MSGC active areas, both 200 and 400 μm pitch, were defect-free for the last gold on Upilex devices received from PPM. Of the remaining 20% there was usually only one defect which resulted in the loss of one or more of the anodes.

Masks

Figure 4.4 shows the details of the four masks used to produce the MSGC prints discussed in this thesis. They have been labelled as mask I through mask IV, and these labels will be referred to throughout the remainder of the thesis. Table 4.4 lists the pitch, number of anodes, number of patterns per print, and the widths of the anodes and cathodes for the four different masks. The masks, both masters

Mask	Pitch (μm)	Number of Anodes	anode width (μm)	cathode width (μm)	number of patterns
I	200	24 (1x24)	15	70	1
	400	12 (1x12)	20	80	
II	200	48 (6x8)	15	70	4
	400	24 (3x8)	20	80	
III	200	80 (8x8+16)	12	88	1
	400	40 (8x3+16)	20	88	
IV	200	80 (8x8+16)	12	88	2
	400	40 (8x3+16)	20	88	

Table 4.4: Mask geometries for the plastic MSGCs.

and submasters, were produced at PPM, and were made of chromium on glass. Prints on the plastics were made using the submaster masks. Note that masks I and III were either 200 or 400 μm pitch, while masks II and IV had patterns of both pitches. The table gives the total number of anodes and the grouping if any. For instance the 400 μm pitch mask III and IV prints had 16 individual anodes and eight groups of three anodes each. A rule-of-thumb which has been

used in MSGC geometries is that 50% of the active area should be metallized. The sum of the anode and cathode widths should thus equal the anode-cathode gap, $w_{subs} = w_{anode} + w_{cath}$. This “rule” has been suggested by numerical simulations [31] [65] and has been generally confirmed by a number of groups. The 200 μm pitch designs followed this rule, while the 400 μm pitch patterns had only 25% of their surface metallized.

Figure 4.4: Mask designs for the plastic MSGCs.

Wet Etch

In the wet-etch process the substrate was coated with metal followed by positive photoresist. The photoresist was exposed to ultraviolet (UV) light though

a mask of the desired MSGC pattern. The exposed photoresist and underlying metal were etched away leaving the MSGC electrode structure. The etching agents depended on the metals used, but included strong acids. The prints produced with wet-etch processing generally had excellent edge quality and electrode uniformity.

One fear was that the strong etchants might alter the surface of the MSGC substrate, and in particular modify the surface resistance. MSGC prints were obtained from PPM on white Tedlar using the wet-etch method with aluminum metallization. These MSGCs worked well, as will be described in Chapter 5, and there was no etching of the substrate surface. Subsequently, gold on Tedlar prints were produced at PPM, and there were initially problems with etching of the Tedlar surface as shown in Figure 4.5. These images can be compared directly with those of Figure 4.2.

Figure 4.5: SEM images of Tedlar after etch damage (a) 7000 X (b) 20000 X.

The prints had severe charging problems and the gain dropped rapidly with low intensity ^{55}Fe X-rays to the point that no signals were seen after a few seconds of operation. The etching problem was solved by changing the gold-etching agents, and later gold prints had unaffected Tedlar surfaces.

All gold on Tedlar prints produced by wet etching had excellent adhesion, and were essentially defect-free. PPM also produced high-quality gold on Upilex MSGC prints using both unimplanted and ion-implanted material. Implanted

wet-etch prints were used at the TRIUMF beam test, and provided much of the significant results described in later chapters.

Liftoff

In the liftoff method the substrate was coated with photoresist and exposed using the MSGC mask. Using an image-reversal process (oxide stencil) a negative image of the MSGC electrode pattern was created in the photoresist. The unexposed photoresist was removed using reactive-ion etching, and metal deposited over the entire surface. The print was then washed in resist solvent, commonly acetone, which removed the unwanted interelectrode metal and left the MSGC electrode pattern. The lift-off techniques produced MSGC prints with excellent edge quality and electrode uniformity, however it was somewhat more difficult to achieve low defect density with this method.

In some cases, with implanted Upilex substrates, an initial thin oxide layer was used in an attempt to protect the plastic from the reactive-ion etch. This protective layer was removed using hydrofluoric acid prior to the metallization. On occasion the Upilex MSGC prints appeared to have surface resistivities much greater than expected for the known degree of implantation. Given the production process there were three distinct possibilities: The oxide layer may have not provided the desired protection during the etch. The acid may have affected the implanted layer as it was being used to remove the oxide coating. Some oxide may have been left under the electrodes, creating an insulating barrier between the metal and the low resistance implanted surface.

Many gold on implanted-Upilex prints were made completely in-house at Spire using contact printing and the liftoff technique. In other cases HTA, Etalon, and PPM were used by Spire on a contract basis for different steps in the process such as the resist application, exposure, etching, and metallization. The final resist removal was normally done at Spire. HTA also had the ability to produce the large masks required for the SDC.

4.2 Inspection

Detailed inspections of the MSGC prints were important to quantify the results from new production processes, especially in the initial contacts with the manufacturers. Measurements of the surface resistivity had to be made to track this critical MSGC parameter which was dependent on factors including implantation dose and specific conditions used in the fabrication. The inspections were also critical in understanding how given print characteristics corresponded to MSGC performance, and in learning how the plastic MSGCs were damaged or aged during use. The prints were examined using various optical microscopes and a scanning-electron microscope.

4.2.1 Surface Resistivity Measurement

For surface-modified polyimides the measurement of the surface resistivity was needed to ensure that this was in the desired range for stable high-flux MSGC operation. Two different methods were used to measure this resistivity. The most direct way used the measured currents drawn by the high voltage cathode supply when the MSGC print was installed in a MSGC test chamber. The other method involved evaporating additional electrodes on to the substrate or, when available, using the test electrode structures incorporated in the mask design. Mask III included a pair of metallized "bulls-eyes" and Mask IV had two test structures to facilitate the measurement of the surface resistance. These electrodes were then used in conjunction with a HP 4329A high-resistance meter to determine the surface resistivity. Both techniques, which are discussed further below, gave results which were in agreement with each other to within an order of magnitude.

MSGC-determined Resistivity

Using the actual MSGC print to determine the surface resistivity of the substrate was straight-forward, and intuitively the best means for making the measurement. This is because the resistance of most concern in the operation of a

MSGC is that present when the detector is working with the real high voltages applied to the electrodes, and with the actual gas mixture. The resistance was obtained by using the current monitor of the high-voltage supply connected to the cathodes of the MSGC. Given the geometry of the electrodes, specifically the anode-cathode separation, the length of the active area, and the number of anodes connected to ground, a value of the surface resistivity in $\Omega/\square$ could be obtained. Resistivities greater than $10^{16} \Omega/\square$ gave monitored currents outside of the measurable range, but for prints with "correct" values of $10^{11} - 10^{15} \Omega/\square$ the results were very consistent. Figure 4.6 shows the measured surface resistivity across a $200 \mu\text{m}$ pitch ion-implanted Upilex MSGC print.

Figure 4.6: Surface resistivity across $200 \mu\text{m}$ pitch ion-implanted Upilex MSGC.

Note the small difference between the electrodes in the groups of eight compared to the individual anodes. This can be attributed to differing degrees of end effects. Most frequently a single value for the surface resistivity of a MSGC print was obtained by connecting the entire print (grounding all the anodes) when the MSGC was mounted in its test chamber. The cathode supply current was measured with no incident particle flux. In this case the quoted value simply corresponded to cathode voltage divided by the measured current and the number of squares for the particular geometry. For MSGC masks III and IV the $200 \mu\text{m}$ pitch patterns have $0.160 \square$ and the $400 \mu\text{m}$ pitch patterns have $0.117 \square$.

Evaporated-Electrode Resistivity Measurement

This method was designed to test the suitability of the ion-implanted polyimide surface resistivity prior to the lithography. It also proved useful in determining whether or not process steps in the lithography had altered the surface resistance and, most recently, in the characterization of Ni-NiO coatings and Inconel oxide coatings. The method consisted of evaporating parallel 3 cm long aluminum electrodes, spaced 0.5 mm apart, on the substrate using an Edwards E12E coating unit. The sample was installed in a gas-tight chamber which also provided shielding against electrical noise. Inert gas (nitrogen or argon) was flowed over the sample and the surface resistivity was measured using the high-resistance meter.

4.2.2 Scanning-Electron Microscope Inspection

A JEOL Model 6400 scanning-electron microscope (SEM) was used extensively to study the quality of the MSGC prints and to inspect the prints after they had been used in the laboratory or in a beam test. In addition to electron imaging the SEM also was capable of X-ray elemental analysis with a 133 eV energy resolution. In this mode the X-rays produced in an e-beam excited volume, typically $2\text{ }\mu\text{m}$ wide by $0.2\text{ }\mu\text{m}$ deep, were detected by a germanium detector and the elements identified using the characteristic X-ray lines. The SEM stage had 7 cm of travel in either direction which made it possible to examine the entire active area of mask III and mask IV MSGC prints. The stage could also be tilted to facilitate the inspection of the edges of the MSGC metallization and to obtain an estimate of the thickness which could be compared to the value derived from resistance measurements.

For high-magnification SEM imaging, that is anything in excess of 200 X, the samples had to be coated with a thin gold-palladium layer in order to prevent electron charge-up of the surface. This coating, between 15 and 20 nm thick, was not essential for the X-ray analysis mode of operation. The anode-like strips

included in the test structures of mask IV prints were designed to allow the quality of the metallization to be inspected without the need to sacrifice the actual MSGC active areas.

Edge Quality

The edge quality of the MSGC prints was inspected using the SEM. Figure 4.7a and figure 4.7b show the edges of an anode for gold on Upilex prints produced by the liftoff and wet-etch techniques respectively.

Figure 4.7: Edges of anodes on MSGC prints (a) wet etch (b) liftoff.

Breakdown Damage

The SEM was a useful tool in inspecting prints post-test and studying MSGC breakdown effects. These breakdowns, one of the biggest concerns with MSGCs, are a result of the extremely high electric fields at the edges of the anodes and cathodes. The principal mechanism for this damage is thought to be electron emission from the cathode as a result of ion bombardment [63]. The ions generated in the event-induced avalanches at the anodes are accelerated in the high near-cathode field and multiply. The impacting ion cloud creates a damage spot on the cathode edge, and the electrons which return to the anode cause an even larger damaged region on the opposing anode edge. Figure 4.8 shows a SEM image of such a breakdown, which is typical of damage sometimes seen after MSGC operation and which is entirely consistent with the mechanism described above. Electron

emission from the cathode can also be induced by photons. In addition there can be field-effect emission, which is the dominant discharge mechanism in MSGC gas mixtures with a high quencher fraction [66].

Figure 4.8: Typical MSGC damage. An anode is to the right of the image and the edge of a cathode is on the left.

Of all the different types of print tested to date the nickel-oxide coated MSGCs, fabricated on both Tedlar and Upilex, have shown the least amount of breakdown damage. One recent Ni-NiO print showed little or no evidence of breakdowns even after the equivalent of 7 years of running in the ATLAS environment [62]. This is unlike ion-implanted Upilex MSGCs which, in some cases, showed a substantial number of breakdowns after extended testing in the laboratory or in test beams.

4.2.3 Optical Inspection

The MSGC prints were inspected optically using two variable magnification Nikon binocular dissecting microscopes as well as a video microscopy inspection station. The dissecting microscopes were most often used for quick looks at the MSGC active areas during the course of laboratory testing while the latter facility was used primarily to perform detailed print quality characterization prior to testing. Each binocular scope had a magnification which could be varied between ten and forty times, and was equipped with a fibre-optic light source. In addition to

simply observing the MSGC prints many other operations were done using these dissecting microscopes. These included the cutting of shorter anodes when necessary as well as the application of end-passivating Humiseal or epoxy coatings. Prior to the use of the heat-seal connectors, as described in section 4.3.1, the optical magnification was also required to make electrical connections to the MSGC contact pads.

The video inspection station was located on a Class 100 laminar flow bench within a Class 1000 clean-room. It consisted of a Panasonic WV-1850 video camera and WV 5360 monitor used with a Koristka R4 microscope with a customized sample stage. The video camera was coupled to the microscope objective using a relay lens.

Figure 4.9: Video image of 200 μm pitch Upilex MSGC.

Illumination was provided by a fibre-optic light unit. Digital sample position read-out was obtained from a pair of Heidenhain VRZ 181 bidirectional counters. This position information facilitated the recording of defects which could be returned to after MSGC operation to investigate if these defects were sources of high-voltage breakdowns.

4.3 MSGC Test Chambers

At least five different generations of test chambers were developed for testing the plastic MSGC prints. Details will be presented on the latest of these chambers since this was used at the CERN and TRIUMF beam tests and for much of the laboratory work with Upilex MSGCs. A total of six chambers of this type were designed and built at the Science Technology Center (STC). The chambers have also been used by the amorphous silicon MSGC group in Montreal and the MSGC group at Purdue University.

The chamber was designed to operate using MSGC patterns from either a mask III or IV print, that is either a 200 μm or 400 μm pitch device. These patterns have a total of 24 channels of anode readout. One of the important aspects of the test chamber design was its modularity and relative simplicity. This was particularly valuable at the beam tests. The MSGC print was mounted on a G-10 fibreglass printed circuit (PC) board, shown in Figure 4.10, which contained the high voltage filtering and current-limiting components.

Figure 4.10: MSGC printed circuit board.

The simple RC low-pass T-filters had a 20 kHz cut-off frequency designed to attenuate switched-mode power supply noise and RF interference. Large 1 M Ω

resistors limited the possible current drawn by discharges in the MSGC. Although current-limited high-voltage supplies were used the cabling (50- Ω RG-58 coax) had sufficient capacitance that this added protection was required. The PC support board also provided a backplane and an edge connector for anode readout.

The support board was sandwiched between two aluminum plates and the entire assembly was held together by six screws. Dowel pins ensured correct alignment between the components. One aluminum plate contained a 25 μm thick mylar window and a drift electrode which was 85 μm thick steel mesh with a 50% open area. A Viton O-ring in this plate defined the gas volume and sealed against the G-10 support board. High voltage was supplied to the drift mesh by a spring which contacted a pad on the support board. The drift gap was 4.0 mm. Figure 4.11 shows the assembled test chamber. The readout electronics, as used in the beam tests, are also shown in the figure.

Figure 4.11: Test chamber for mask III and IV MSGC prints.

4.3.1 Connection Techniques

Heat-Seal Connectors

Connections to the plastic MSGC prints were most often made using a Heat-Seal Connector (HSC) manufactured by Nipon Electronic of Japan, and distributed by Elform of Reno, Nevada. The connector consisted of gold-nickel microsphere traces within a flexible epoxy matrix, and came in the form of sheets which were cut to the required length and width. By applying a combination of heat and pressure, using an Elform-supplied press, connections between the plastic MSGC print and its supporting printed circuit board were made quickly and simply. Figure 4.10 shows the Elform connectors making contacts with the anodes and cathodes of a Upilex MSGC print.

Conductive Epoxy

Early plastic MSGCs were connected using thin wires and various types of conductive epoxy and conductive paint. Before the heat-seal connection technique was developed, most of the MSGC prints were connected using conductive epoxy. Fine wires were soldered to pads on the PC boards and the other ends of the wire were fixed to the pads on the MSGC print using E-Kote 3040 silver-filled conductive epoxy. This had to be done under a microscope and required a high degree of dexterity.

Unfortunately the conductive epoxy was found to flake. Some of these flakes ended up on the active area, where they caused shorts and hastened the demise of several MSGCs detectors. This was particularly true with 200 μm pitch detectors, where the anode to cathode gap of 50 μm was comparable to the typical sizes of the flakes observed. The flaking depended on the consistency of the epoxy at the time it was initially applied. Non-conducting epoxy was subsequently applied as a sealant to the lumps of conducting epoxy making the connections.

Mechanical Contacts

The chamber shown in Figure 4.12 was designed to facilitate testing of mask II MSGC prints. It used spring-loaded pins to make electrical contacts with the anode and cathode pads. This made the installation of a new print possible in a matter of minutes. The mechanical contact method was possible because no anodes in the mask II design were individually read-out. All the anodes were ganged-together in groups of eight.

Figure 4.12: Test chamber for mask II MSGC prints.

Wire Bonding

Attempts made using wire-bonding facilities in the Carleton Department of Electronics were unsuccessful due to the lack of rigidity of the plastic MSGC surfaces. Connections to specially thickened gold contact pads on Upilex, using ultrasonic wire-bonders, have recently been demonstrated by other MSGC groups.

4.3.2 Special Treatment of Electrode Ends

One problem with all MSGCs are the high-field regions at the ends of the active area where the anodes and cathodes end. Masks I and II have anodes and cathodes with simple rectangular ends. These ends were found to be incapable

of withstanding the voltages needed to obtain significant gas gain over the entire MSGC active area. With these masks it was necessary to apply a passivating coat of Araldite AW106 epoxy resin (HV953U hardener), manufactured by Ciba-Geigy, over the anode and cathode end regions. This epoxy, which remained flexible when cured, was found to be superior to other epoxies such as "5-minute Epoxy".

Mask III and IV prints had rounded ends on the cathodes and anodes. Although this was found to be an improvement over the rectangular ends, and operation was possible at low gas gains, the ends had to be passivated against breakdowns in order to achieve higher gains. Electric-field calculations [67] [68] have confirmed the existence of high electric fields even with the rounded-cathode configuration. Breakdown at the ends was clearly seen by both optical and SEM inspection, and in some cases of severe breakdown the damage was significant enough to be also seen with the naked eye.

All the Upilex MSGC prints discussed in this thesis were passivated at the ends using Humiseal 1B15 acrylic coating prior to testing. One concern with passivation is that the coating material should not contribute to the accelerated aging of the MSGCs when reactive gases such as DME are used. Humiseal is not expected to be adequate for this long-term operation, and the ends of Carleton-CRPP MSGCs are now coated with Epotecny E505 epoxy resin, which has been used at CERN during ageing studies.

Chapter 5

Laboratory Testing

This chapter presents the results from testing the plastic MSGCs in the laboratory using X-rays. The initial sections give details of the electronics, gas system, and gain calibration techniques. Results include the relative performance of different MSGC gases, rate dependence, and gain uniformity. The voltage dependence of the gas gain of Tedlar MSGCs and Upilex MSGCs are presented to illustrate the differences between their conduction mechanisms.

5.1 Hardware

High voltages were supplied to the MSGCs by 10 kV Bertan 1792N, diode-switched, current-limited, power supplies. These supplies were monitored using digital multimeters and outputs with 1 mV/V voltage sensitivity and 10 mV/ μ A current sensitivity. The monitors were verified using 1 G Ω and 1 T Ω resistors, and were accurate for any setting of the current-trip control other than the 1 mA and 0.1 μ A trip limits. The current limits were adjusted to the current drawn by the substrate of the MSGC under test and were typically 1 μ A or 10 μ A. If the currents exceeded 80% of the set value, such as might occur during a breakdown between the anodes and cathodes, the high voltage was automatically shut down. A high-precision multimeter (HP 34401A) was used to directly measure MSGC currents including the flux-induced currents produced during high-rate testing with the X-

ray generator. Amplified MSGC signals were viewed on a 1 GHz Tektronix 7104 analog oscilloscope and a 500 MHz, 1 GS/s, Tektronix TDS 540 digital scope.

5.1.1 Read-Out Electronics

The MSGCs were read-out using single-channel charge-sensitive preamplifiers followed by main research amplifiers. The most common pairing was an EG+G Ortec 142PC preamplifier and an EG+G Ortec 450 main amplifier. The amplified MSGC signals were then input to one of the following three multi-channel analyzers (MCAs), a LeCroy 3001 qVt, an EG+G Ortec 916A, or an Aptec 604. The latter two MCAs were cards installed in personal computers. The Ortec card, with a 2048-channel memory, ran with MAESTRO II MCA emulation software on a PC-AT. The Aptec card, with a 4096-channel memory, was in a 33 MHz 80486 PC. Both the LeCroy qVT and the Ortec MCA required gates, and this gating was provided using discriminators and gate generators. A typical arrangement is given in Figure 5.1. The measurements made using the Aptec were simpler in that an internal gate was generated and most of the data were acquired with this system.

Figure 5.1: Arrangement to readout MSGCs using LeCroy qVt.

5.1.2 Signal Calibration - Gas Gain

In order to determine the MSGC gas gain the electronics were calibrated using a known impulse of charge at the input of the preamplifier. This charge was

of the form of a step voltage from a fast pulser, most often an EH Research 137 pulse generator (2 ns pulse risetime) on the 1 pF preamp test input capacitor. The dependence of the apparent gain on the shaping time of the read-out electronics is illustrated in Figure 5.2. This data were collected using an Ortec 142PC preamplifier, Ortec 450 main amplifier, and a 400 μm pitch Upilex MSGC.

Figure 5.2: Gain versus shaping time for 400 μm pitch MSGC.

The most consistent definition of gas gain, for the purposes of comparing one detector to another, is the ratio of the total avalanche charge divided by the number of initial ionization electrons. This would be measured for a shaping time longer than the total ion anode-drift time (several μs), or by using the average flux-induced current. For the plastic MSGCs there was 60% difference between this gain value and that obtained using a typical shaping time (0.25 μs). This ratio was measured experimentally and was also confirmed using the MSGC simulations discussed in Chapter 7.

Most of the MSGC gas gain results presented in this chapter were obtained using ^{55}Fe sources. The gain in this case is the charge corresponding to the main 5.9 keV peak, obtained from a pulser-calibrated ^{55}Fe spectrum, divided by the average number of initial electrons for the particular gas mix used. For example in the case of P-10 gas an 5.9 keV X-ray creates an average of 223 electrons.

5.1.3 Gas System

The gas system for the MSGCs under test was simple and flexible. All testing was done at atmospheric pressure, with flow rates through the gas microstrip chambers being typically 0.1 ℓ pm, corresponding to two volume changes per minute. Gas mixes were obtained from premixed bottles using two-stage pressure regulators. Argon-isobutane mixes were also created by mixing pure gases using a flow-mixing station. All gases used were "research" grade with the argon having a purity of 99.95%. No additional filtering of the gas was performed except during one mixing trial when oxygen and water-vapor filters were used. Gas flow was measured by small ball-in-tube flowmeters located between the supply and the MSGC test chambers.

Leak-testing was performed using Matheson gas sniffers or by pressurizing the MSGC chamber with a few cm of water pressure using a simple U-tube manometer. With the latter test the chamber was deemed to be sufficiently gas-tight if the drop in pressure was found to be less than a couple of mm of water-equivalent pressure per hour.

5.2 Gain Results - Gas Mixes

Table 5.1 summarizes the mixes used in laboratory testing of the MSGCs. P-10 gas is a standard MWPC gas mix and it was also one of the most frequently

gases	ratio	description
Ar-CH ₄	90-10	P-10
Ar-CH ₄ -iC ₄ H ₁₀	88-10-2	OPAL mix
Ar-iC ₄ H ₁₀	90-10	beam tests
	80-20	
Ar-DME	90-10	
	80-20	
CF ₄ -iC ₄ H ₁₀	80-20	

Table 5.1: Gas mixes used in lab MSGC testing.

used gas mixes in early plastic MSGC research [69] [70]. Unfortunately it was

inappropriate for MSGC development since it does not provide adequate quenching for typical MSGC geometries and operating voltages. In addition, it has relatively small gas gain compared to other argon-based mixes.

The standard gas mix for much of the MSGC testing, both in the laboratory and during the beam tests, was a 90-10 argon-isobutane mix. Tests with a single-wire proportional tube found that a 90-10 argon-isobutane mix gave higher gains than a P-10 mix, as shown in Figure 5.3.

Figure 5.3: Argon-methane and argon-isobutane mixes in proportional tube.

Isobutane is a superior quencher to methane, and much more appropriate for MSGCs. Even small quantities of isobutane, such as in the OPAL mix, 88% argon, 10% methane, and 2% isobutane, were found to be of benefit in increasing the MSGC breakdown voltage.

Figure 5.4 shows the relative gas gain as a function of cathode voltage for a 400 μm pitch Upilex MSGC with $V_{back} = -600$ V and $V_{drift} = -2000$ V using four different gas mixes. The superiority of both isobutane and DME over methane was clear. A relative gas gain of one in the figure corresponds to a gain of 1000 measured using a 142PC-450 amplifier chain with a 0.25 μs shaping time.

Figure 5.4: Gas gain of Upilex MSGC for different gas mixes.

The energy resolution of a MSGC can be quantified by measuring the ratio of the full-width at half maximum (FWHM) of the main X-ray peak to the peak energy itself. For all the tested gas mixes and MSGCs, both Tedlar and Upilex, the energy resolution was between 15% and 20%. Figure 5.5 shows typical ^{55}Fe spectra for different gas mixes. The escape peak for argon-based mixtures provided a qualitative measure of MSGC performance since its position with respect to the main X-ray peak was fixed. The desired signal-to-noise ratio was one such that the escape peak was clearly resolved and distinct from electronic noise. Such noise was always present to some extent in the lower channels.

As discussed in Chapter 3 the escape peak was due to the argon. There was no escape peak in the 80-20 CF_4 -isobutane gas mix which was the only non-argon-based mixture used in the MSGC testing. In case of the spectrum shown in the figure the 5.9 keV X-ray peak was sitting on the noise. This illustrated one problem with the use of this mix with the MSGCs, namely low gain at the voltages which could be applied before breakdowns. For a 200 μm pitch MSGC argon-based mixes required cathode voltages of about 500 V, while the CF_4 -isobutane mix required more than 700 V.

Figure 5.5: ^{55}Fe spectra for different gas mixes.

5.3 General MSGC Testing

This section provides some interesting results obtained during the MSGC testing which do not fit into any distinct category but were significant.

5.3.1 Single-Anode Operation

Superior X-ray energy resolution was achieved when only a single MSGC anode was grounded (and read out) with all the remaining anodes left floating. In this mode, the ^{55}Fe energy resolution was found to be less than 10%. Figure 5.6 shows such a “single-anode” spectrum obtained with a 90-10 argon-isobutane gas mix.

Figure 5.6: ^{55}Fe spectrum with single grounded anode.

Unlike normal MSGC operation, where the charge in any given X-ray generated primary electron cloud is spread over several anodes, all the charge in single-anode mode is funneled to the one grounded anode. The floating anodes charge up to the negative cathode voltage creating "super-cathodes" as illustrated in Figure 5.7. The anode is hence surrounded on either side by this plane of negative high voltage and all ionization electrons are collected on this anode. A device fabricated with a single anode-super cathode structure may be useful in other applications.

Figure 5.7: Voltages in the "single-anode" mode.

5.3.2 Collimated ^{55}Fe Source Profile

A 200 μm pitch, gold on ion-implanted Upilex, MSGC was used to obtain a profile of the collimated ^{55}Fe source used during much of the testing. This source used a 1 mm diameter hole in a 20 mm long aluminum cylinder to provide the collimation of the 5.9 keV X-rays. The entire MSGC test chamber was translated

with respect to the fixed source using a micrometer stage. The count rate for one of the individual anodes was measured as a function of MSGC position, with a discriminator used to select pulses corresponding to the main ^{55}Fe peak. The gas mix was P-10, and the operating voltages were $V_{\text{cath}} = V_{\text{back}} = -430$ V, $V_{\text{drift}} = -800$ V.

Figure 5.8: ^{55}Fe source (a) profile (b) image assuming radial symmetry.

Figure 5.8a shows the resulting profile and figure 5.8b is an image obtained by assuming radial symmetry and contouring the count rate. This is a precursor of the scanned images now being obtained with a high-resolution medical-imaging system.

5.3.3 Gain Uniformity

Figure 5.9 shows the relative gas gain versus position when the collimated ^{55}Fe source was scanned across the middle of the active area of a $400\ \mu\text{m}$ pitch Upilex MSGC. The operating voltages were $V_{\text{cath}} = V_{\text{back}} = -680$ V, $V_{\text{drift}} = -2300$ V, and the gas mix was 90-10 argon-isobutane. All the anodes were ganged together and read out using a Ortec 142PC/450 amplifier chain and the Aptec MCA. The central 10 mm of the active area was uniform to within 5% in gain. The gain in the outer 2 mm on each edge of the print could be flattened to that in the central region by setting the guard voltage to $V_{\text{cath}} = -340$ V (i.e. at half the cathode voltage). The guard electrodes were located on each side of the active area (refer to the mask designs given in Chapter 4, section 4.1.6) and were normally set equal to

the cathode voltage. The heat-seal connectors, used to make electrical connections to the MSGC, did not withstand high voltages between their traces and to vary the guard voltages required using a split connector.

Figure 5.9: Gain uniformity for 400 μm pitch Upilex MSGC.

5.3.4 Backplane Readout

An advantage of thin plastic MSGCs over thick substrates is the possibility of reading signals off the backplane as a means of obtaining 2D information. This has been demonstrated by the group at Purdue, whose 300 μm pitch detectors fabricated on 125 μm thick, ion-implanted Upilex were tested along with Carleton-CRPP devices during the TRIUMF beam test (see Chapter 6).

A segmented backplane MSGC has yet to be implemented locally, however, the 5 cm $\times$ 2 cm backplane of a 200 μm pitch, $10^{12} \Omega/\square$ resistivity, Upilex detector was read out using a 100 pF blocking capacitor and Ortec 142PC-450 amplifier chain. When tested with an ^{55}Fe source at $V_{\text{cath}} = V_{\text{back}} = -450\text{V}$, $V_{\text{drift}} = -1300\text{V}$, and a 90-10 argon-isobutane gas mix, the backplane signals were found to be 2.7 times smaller than those on the anodes. For the Purdue MSGCs the signals were a factor of 5.2 times smaller on the 700 μm wide backplane electrodes than on the anodes. As thin a substrate as possible must be used to obtain backplane signals large

2 OF 2

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enough to be useful, and this is why the Carleton-CRPP group started production on 50 μm thick substrates.

5.4 Rate Capability

As discussed in the previous two chapters to operate MSGC's at very high rates the surface resistivity of the substrate must be about $10^{11} \Omega/\square$. This was the motivation for using ion-implantation or thin coatings to reduce the surface resistivity. The X-ray generator was used to study the high-rate performance of the ion-implanted Upilex MSGC's and the results are briefly summarized here. The studies are described in greater detail in [32] [62] [71]. The results were consistent with models where charging (section 3.3.1) was the dominant mechanism. Figure 5.10 shows the relative gas gain for a 200 μm pitch ion-implanted Upilex MSGC as a function of the photon flux. This MSGC demonstrated a hundred times better rate capability than a MWPC.

Figure 5.10: Rate capability of 200 μm pitch Upilex MSGC.

5.5 Tedlar Voltage Dependence

The first plastic MSGC operated at Carleton-CRPP was manufactured at CERN on white Tedlar. It had a pitch of $200\text{ }\mu\text{m}$ and had aluminum metallization. ^{55}Fe signals were obtained with P-10 gas mix at voltages of $V_{\text{anode}} = +530\text{ V}$, $V_{\text{cath}} = V_{\text{back}} = 0\text{ V}$, and $V_{\text{drift}} = -200\text{ V}$. The drift gap was 5.5 mm . The ^{55}Fe spectrum, shown in Figure 5.11, was acquired using the qVt system shown in Figure 5.1. All 24 anodes were ganged-together. The energy resolution was 20% and the gas gain was 300.

Figure 5.11: First local ^{55}Fe MSGC spectrum.

A $100\text{ }\mu\text{m}$ pitch, gold-on-Tedlar MSGC, produced by PPM, was tested with P-10 gas mix using different operating voltages. The same voltage dependence was found for all Tedlar MSGCs, both $200\text{ }\mu\text{m}$ and $400\text{ }\mu\text{m}$, and all gas mixes. Only the absolute gain values were different, as these depended on the particular MSGC geometry, voltages, and gas mix. Figure 5.12 shows the relative gas gain as a function of the cathode voltage, where for all data points the cathode voltage was equal to the backplane voltage. The drift voltage was $V_{\text{drift}} = -1000\text{ V}$, and a relative gain of one corresponds to a measured gas gain of 2000. The gas gain was an exponential function of the cathode voltage.

Figure 5.12: Cathode voltage dependence for Tedlar MSGC.

Figure 5.13 shows the relative gas gain as a function of the drift voltage. For this measurement $V_{cath} = V_{back} = -600$ V. The gas gain was linear with the drift voltage.

Figure 5.13: Drift voltage dependence for Tedlar MSGC.

Figure 5.14 shows the relative gas gain versus the backplane voltage for $V_{cath} = -600$ V and $V_{drift} = -1000$ V. Unlike ion-implanted Upilex MSGCs, the Tedlar detectors had a strong backplane dependence.

Figure 5.14: Backplane voltage dependence for Tedlar MSGC.

5.6 Upilex Voltage Dependence

The first Upilex MSGC operated locally was a $400\text{ }\mu\text{m}$ pitch gold-on-Upilex print, produced by Spire, and tested with OPAL gas mix. The voltages were $V_{cath} = V_{back} = -700\text{ V}$, and $V_{drift} = -1500\text{ V}$. Figure 5.15 shows the relative gas gain versus the cathode voltage for a drift voltage of -1500 V , while figure 5.16 gives the relative gas gain as a function of drift voltage for $V_{cath} = V_{back} = -750\text{ V}$. In both figures a relative gain of one corresponds to an actual gain of 200.

Figure 5.15: Cathode voltage dependence for Upilex MSGC.

Figure 5.16: Drift voltage dependence for Upilex MSGC.

Figure 5.17 shows the relative gas gain versus the backplane voltage for a $200\ \mu\text{m}$ pitch, gold-on-Upilex, print tested with P-10 gas at $V_{cath} = -500\ \text{V}$ and $V_{drift} = -1000\ \text{V}$. Note that the gain is totally independent of the backplane voltage, as discussed in section 5.7.

Figure 5.17: Backplane voltage dependence for Upilex MSGC.

5.7 Conduction Mechanisms

The differences between the Tedlar and ion-implanted Upilex MSGCs shown in the previous two sections are due to the conduction mechanisms in the substrates. In a Tedlar MSGC the resistance between the anodes and cathodes is due to the bulk material of the substrate. The MSGC community refers to this type of MSGC as a bulk-conducting MSGC. For an ion-implanted MSGC the surface resistance is essentially all due to the thin conducting layer just below the surface, and this is a surface-conducting MSGC. The differences between the two types of detectors, in terms of backplane voltage dependence and maximum gas gain, can be understood by simply considering the electric fields in the two cases.

Figure 5.18 plots in the same graph the relative gas gain versus backplane voltage for a Tedlar MSGC and a Upilex MSGC, showing the clear difference between the two types of substrates. The low resistivity surface layer in the ion-implanted Upilex effectively screens the gas volume from the high-voltage on the backplane. In the case of Tedlar the backplane voltage contributes to the anode field strength as evidenced by the increasing gas gain with increasing backplane voltage.

Figure 5.18: Backplane dependence for Upilex and Tedlar MSGCs

These backplane voltage effects were confirmed by electrostatic calculations using

programs described in Chapter 7. The screening by a conductive surface layer has been observed in other MSGC's [72] [59].

The insensitivity of surface-conducting MSGC's to the backplane voltage also means that it is harder to achieve high gains as demonstrated by bulk conducting MSGC's (at least at low fluxes). There is a fundamental trade-off between rate capability and gas gain which follows the old maxim ... *you can't get something for nothing*.

Chapter 6

Beam Tests

This chapter presents results obtained from the Tedlar and Upilex MSGCs operating in charged-particle beams. The tests were important for proving the capability of MSGCs in high-energy physics applications, and provided fundamental insight into the detector physics. Table 6.1 summarizes the four beam tests. Three tests were at CERN, while the fourth test was at TRIUMF. As indicated

#	Date	Location	Particle Momentum	MSGC Description	Readout Channels
1	Jun 1992	CERN PS	10 GeV/c	1-400 μm , Al, Tedlar	3
2	Nov 1992	CERN PS	10 GeV/c	1-200 μm , Al, Tedlar	24
3	Jul 1993	CERN SPS	200 GeV/c	3-200 μm , Au, Upilex	48
4	Jan 1994	TRIUMF	130 MeV/c	4-400 μm , Au, Upilex 2-200 μm , Au, Upilex	96

Table 6.1: Summary of the plastic MSGC beam tests.

by the number of MSGC prints and the number of read-out channels the tests were progressively more substantial. The final beam test resulted in the most data, and this test will be discussed in the greatest detail.

6.1 Beam-Test Hardware

The beam tests required additional mechanical and electronic hardware not used routinely in the laboratory testing. Details of the hardware used will be discussed in sections 6.2 through 6.5 where each test is presented.

The key electronic component was the QPA02 amplifier which was used at the final two beam tests. This amplifier was incorporated into the MSGC' simulation, as presented in the following chapter, and is now being used in a MSGC' medical-imaging system under development in the Carleton-CRPP laboratory. The QPA02 is a semicustom, bipolar chip which was designed at Fermilab [73] [74] as a silicon microstrip preamplifier. It is a fast, high-gain, 4-channel, two-stage, transimpedance amplifier which accepts both positive and negative inputs. Pairs of these chips, manufactured at Tektronix, were packaged in chip-carriers, such that 8 channels were available per package. Four of these packages, mounted on double-sided, four-layer circuit boards, provided a total of 32 channels. Note that, as described in section 4.1.6, a mask III or IV MSGC detector has 24 anode signals. Six QPA02 amplifier boards, each measuring $9\text{ cm} \times 11.5\text{ cm}$, were obtained from Fermilab.

The input stage of the QPA02 is a preamplifier consisting of a large area common-emitter transistor, a cascade transistor, and an emitter follower. The second stage is a bandwidth-limited voltage amplifier-shaper with differential output. The impulse gain is set during production by laser trimming resistors in the output stage. Figure 6.1 shows the measured impulse gain for a single QPA02 channel. The gain falls off with increasing charge beyond an input of 10 to 15 fC, corresponding to output signals of 100 to 150 mV. For an effective MSGC' gas gain of 1000 (avalanche gain of 2000) a single electron produces an output of 1.7 mV for a QPA02 gain of 10 mV/fC.

Figure 6.1: Measured charge gain of QPA02 amplifier.

There was some variation in the nominal gains of different amplifier boards used in the MSGC testing, with the measured gains ranging from 8 mV/fC to 15 mV/fC at an input of 10 fC. This variation was attributed to the fact that the QPA02 dies were obtained from two separate production runs. The devices obtained from the later batch consistently had lower nominal gains than those from the earlier one. It was possible that the dies were trimmed to two different configurations. The gain was, however, fairly uniform for all the channels on a given QPA02 board.

The QPA02 requires two supply voltages. V_{cc1} supplies both of the amplification stages, while V_{cc2} powers the output driver transistors. These voltages were kept as high as possible to maintain good charge gain. Optimum performance required $V_{cc1} = +5.5$ V and $V_{cc2} = +3.5$ V. The total power dissipated per channel was 12 mW, and the rms input noise for 20 pF was about 2000 electrons as measured in the laboratory. At the output this noise was 3 mV rms.

The typical impulse response of a QPA02 is given in figure 6.2. For an input capacitance of 20 pF the design specifies a risetime (10% to 90%) of 6 ns, a falltime (10% to 90%) of 12 ns, and a FWHM of 14 ns. The response has a base-to-base width of only 30 ns which, as will be described in section 6.5, had important consequences when combined with the 100 ns drift times typical of 4 mm gap MSGCs using argon-isobutane gas mixes.

Figure 6.2: Measured impulse response of a QPA02 amplifier.

Breakdowns within the MSGC active area would result in high voltages appearing on the anodes and at the QPA02 inputs. A protection board was used to interface each QPA02 board to the MSGC support board. Surface mount capacitors, nominally 1 pF, located on the protection board after the back-to-back protection diodes, allowed test pulses to be applied to each of the QPA02 inputs. These capacitors were useful in debugging the data acquisition system, but because the individual capacitances varied by up to 20% quantitative tests of QPA02 gain were difficult.

Grounding and shielding considerations are critical when using very fast, high gain, amplifiers like the QPA02. The inputs had to be carefully shielded from the outputs to avoid severe oscillations due to feedback. If there was a capacitance of 0.1 pF between the outputs and the inputs then for an output voltage of 10 mV the charge on this stray capacitance equals the original input signal, namely 1 fC. The QPA02 board has multiple ground planes and decoupling capacitors were located as close as possible to the chips. The entire read-out system was designed to minimize pick-up noise from the surrounding environment. Ribbon cables, carrying the differential outputs from the QPA02 amplifiers, were bundled together with layers of copper tape serving as ground planes.

6.2 Test #1, Tedlar MSGC at CERN

The first beam test used the T7 secondary beam in the East Hall at the CERN Proton Synchrotron (PS). This beam had a momentum of 10 GeV/c, and consisted primarily of pions with some protons and electrons. A single 400 μm pitch, aluminum-on-Tedlar MSGC, with three 8-anode groups, derived from a mask II print, was tested using a 90-10 argon-ethane gas mix. The electron drift velocity of this mix was calculated using MAGBOLTZ and found to be 30 $\mu\text{m}/\text{ns}$ at the MSGC drift field of 5 kV/cm. The read-out electronics consisted of a 4-channel LeCroy TRA402 current-sensitive preamplifier, and standard NIM ADC and TDC modules. The LeCroy 402 was a very fast amplifier, with a 3 ns risetime and 5 ns falltime, with a gain of 25 mV/ μA . The timing distribution had a width of 75 ns, which corresponded to the full drift time.

Figure 6.3: Spatial response of 400 μm pitch Tedlar MSGC.

During the beam test only a 1 cm long region of the active area, near the anode contact pad end, produced measurable signals. The collimated ^{55}Fe source was used to obtain the spatial response profile for the MSGC operating with the LeCroy electronics and with a P-10 gas mix. Figure 6.3 shows the results which confirmed the finding at the test beam. This profile was due to the high-resistance of the aluminum anodes, which as mentioned previously, was typical of PPM prints

where sputtering was used for the metallization. The high resistance anodes, combined with the LeCroy amplifiers, meant that events further down the length of the anodes were severely attenuated. The issue of high-resistance MSGC anodes has recently been addressed [75] and the results using this plastic MSGC are in agreement with this analysis.

6.3 Test #2, Tedlar MSGC at CERN

The second beam test was for a $200\text{ }\mu\text{m}$ pitch MSGC made using mask III on Tedlar and having aluminum electrodes. The same CERN beamline used in Test #1 was also used for this test. However, the LeCroy 402 read out electronics were replaced by 24 channels of LeCroy HQV810 charge-sensitive amplifier, implemented using three 8-channel chips. The HQV810 amplifiers had a risetime of 30 ns. The MSGC was mounted in the first of the “modern” test chambers, as described previously in Chapter 5, and used in all subsequent beam tests and laboratory studies.

Figure 6.4: Timing distribution of $200\text{ }\mu\text{m}$ pitch Tedlar MSGC.

The gas mix was 90-10 argon-isobutane, and the gas gain was 3000. The timing distribution, shown in Figure 6.4, had a standard deviation of 18 ns. The trigger

threshold corresponded to six primary electrons. The aluminum resistance was still high and post-test inspection of the MSGC found that several of the anodes were broken (open-circuited).

6.4 Test #3, Upilex MSGCs at CERN

The third beam test [76] was made using three, 200 μm pitch, MSGCs fabricated on ion-implanted Upilex with gold electrodes (using mask III). The readout of each detector consisted of 16 channels of QPA02 amplifiers and a 100 MHz flash-ADC (FADC) system (Struck DL-300). This read-out system was provided by other members of the RD-28 collaboration who were testing 300 μm pitch glass MSGCs in the same 200 GeV/c CERN Super Proton Synchrotron (SPS) M-28 beamline. The mixed particle beam had an intensity which could be varied up to $10^6 \text{ mm}^{-2}\text{s}^{-1}$. The three Upilex MSGCs were mounted on a jig directly upstream of a scintillator telescope and the glass MSGCs. The gas mix was 85-15 argon-isobutane, and the surface resistivities of the MSGCs ranged from 10^{13} to $10^{15} \Omega/\square$. The quality of the MSGC prints, produced using lift-off by Spire, was poor and several of the anodes were deliberately cut so the remaining anodes were able to maintain sufficient high voltage. This resulted in only a small number of consecutive working anodes, which limited the possible data analysis.

One finding was that the plastic MSGCs appeared to efficiently detect the MIPS at rates up to $10^5 \text{ mm}^{-2}\text{s}^{-1}$ with little or no flux dependence. This was unlike the normal glass MSGCs, which showed severe gain loss attributed to charging at all but the lowest fluxes, but similar to the MSGC built on conducting Shott S-8900 glass [77]. Figure 6.5 shows the efficiency of the Upilex MSGCs as a function of the threshold for a beam intensity of $10^4 \text{ mm}^{-2}\text{s}^{-1}$. Data from two of the MSGCs were used to determine the expected hit position in the third MSGC and thereby the efficiency in this detector was obtained. The QPA02 amplifiers were shown to be able to read-out the plastic MSGCs provided that the gas gain, as measured using ^{55}Fe in the laboratory, was about 1000. The beam test provided

valuable experience with operating multiple MSGCs with a fast, QPA02-based, data acquisition system (DAQ). As will be described in the next section, this paid significant dividends at the subsequent beam test.

Figure 6.5: Efficiency of 200 μm pitch Upilex MSGCs.

6.5 Test #4, Upilex MSGCs at TRIUMF

The fourth beam test [78] was performed in the M13 beamline at the TRIUMF cyclotron using ion-implanted Upilex MSGCs. These MSGCs, with pitches of 200 and 400 μm , were fabricated by PPM using wet etching and were of excellent quality. Two different atmospheric-pressure gas mixtures were used during the beam test. The MSGC prints had been characterized in the laboratory prior to the beam test using a 90-10 argon-isobutane mix, and most data were collected using this mix. In all cases the flow rate through the MSGC chambers was 0.1 μpm . With argon-isobutane mixes the fast shaping time of the QPA02s meant that only a fraction of the total ionization charge was seen. As discussed in section 6.5.6, and in Chapter 7, this had important consequences.

The MSGCs were mounted on a jig which had a total of seven mounting positions. Ion-implanted Upilex MSGCs from Purdue (with backplane readout)

and amorphous silicon MSGCs from Montreal were tested along with the Carleton-CRIP detectors. The central position on the jig was equipped with a translation-rotation stage which allowed the MSGC in this location to be rotated with respect to the beam axis and the other detectors. The jig was surveyed into position such that the fixed MSGCs were perpendicular to the beam with the anodes being vertical. This meant that the beam illuminated every anode in the active area of each MSGC.

The momentum of the mixed e, π, μ beam was 130 MeV/c. The beam composition was approximately $e : \pi : \mu = 10 : 80 : 10$. Two 5 mm $\times$ 5 mm scintillators served to define the beam. Electron events could be specifically selected via time-of-flight by including a suitably-delayed cyclotron RF signal in the scintillator trigger. The total particle rate was 10^5 s^{-1} with a horizontal beam width of 2 cm and a vertical height of 1 cm. The average particle flux was about $10^3 \text{ mm}^{-2}\text{s}^{-1}$. To minimize multiple scattering in the low momentum beam the chambers were oriented as shown in Figure 6.6 to reduce, as much as possible, the material between the detection planes.

Figure 6.6: Arrangement to minimize multiple scattering.

The first chamber was mounted in reverse, with its G-10 support board facing the beam. The second chamber had a hole cut in its support board behind the active

area of the MSGC. This eliminated all support materials between the active areas of the three plastic MSGCs used to obtain efficiency and spatial resolution results.

Table 6.2 lists the materials used in the chambers and gives their radiation length contribution. The rms multiple-scattering angle for a particle with momentum, p (in MeV/c), and velocity, βc , is

$$\sigma_{ms} = \frac{14.1}{\beta cp} \sqrt{\frac{L}{L_R}} \quad (6.1)$$

For a normal chamber the total radiation length was 1.54%, and the rms multiple-scattering angle for 130 MeV/c electrons was 13.5 mrad. For the central chamber, with the support removed, the radiation length was 0.3%, which gave an electron scattering angle of 5.7 mrad. The major contributor to this was the stainless steel drift mesh which had a thickness of $85 \pm 15 \mu\text{m}$ and 50% open area. This scattering was important in terms of the analysis of the data in terms of spatial resolution and will be discussed further in section 6.5.5. A schematic of the data

material	radiation length L_R (cm)	thickness L (μm)	L/L_R (%)
mylar	28.6	25	0.0087
steel	1.76	42.5 ± 8	0.241 ± 0.045
gold	0.55	0.025	0.00045
Upilex	27.5	125	0.0455
copper	1.43	60	0.420
G10	19.4	1600	0.825
TOTAL			1.54

Table 6.2: Materials used in the MSGC test chambers.

acquisition system is shown in Figure 6.7. The readout of the MSGCs was done with 96 channels of FADC (Struck DI -305), housed in a single custom crate. This system read up to four MSGCs with 24 channels each. The sampling frequency was 100 MHz, and the FADCs had an 6-bit non-linear dynamic range. To avoid using a large number of delay cables the FADCs were operated in a common-stop mode.

An event-time uncertainty of up to one sampling interval (10 ns) was introduced because the sampling clock was asynchronous with the trigger. After each trigger, the relevant data from the FADC buffers were read into a VME processor and selected segments (400 ns long) were stored on Exabyte tapes for off-line analysis. The pulse shapes for all of the 96 channels could also be inspected on-line on an event-by-event basis. The readout was limited to about 70 events per second by the tape-writing process.

Figure 6.7: DAQ system used at TRIUMF.

6.5.1 Noise

As discussed previously, fast, high-gain amplifiers such as the QPA02 are sensitive to environmental noise. During some runs at TRIUMF noise, with a distinct frequency, was evident. This noise, with greater amplitude than the normal white noise levels, was present to some extent on several of the QPA02 boards. Figure 6.8 shows the frequency spectrum of this noise obtained by averaging the transforms of the FADC pulses from ten individual anodes. The frequency of this noise was 18.5 MHz. The fundamental TRIUMF cyclotron RF is 23 MHz.

Figure 6.8: Frequency distribution of noise.

6.5.2 Particle Type and Beam Polarity

During initial set-up the beamline was run with positive particles, nominally consisting of e^+ , π^+ , and μ^+ . Figure 6.9a shows the beam particle signals, as captured on a digital oscilloscope, in the first scintillator compared to the signals in a 400 μm pitch Upilex MSGC behind it.

Figure 6.9: (a) Energy loss differences between particles (b) Event where two particles were detected on the same MSGC anode.

As previously discussed in Chapter 3, regardless of particle polarity, the pions and muons in the beam deposited significantly more energy than the electrons in both

the scintillator and in the MSGC. In the scintillator there were two distinct bands of pulse heights, with the bigger pulses corresponding to the pions. Although, as expected, the energy resolution in the MSGC was not as good as in the scintillator, there also appeared to be two bands. The upper trace in Figure 6.9b is from the scintillator and it shows a positron pulse followed by another pulse 88 ns later. This is consistent with the 86 ns corresponding to two cyclotron micropulses (43 ns separation in these pulses), and suggests that the second pulse was also a positron. Note that the transit time difference for the 11 m between the target and the centre of the MSGC test jig was 17 ns for 130 MeV/c electrons and pions. The lower trace in the figure shows the two particles being detected by a single anode of the MSGC.

When running with the positive beam there were frequently events where the signals in the MSGCs were so large that they could be seen as fluctuations of the current-trip indicator needles on the high-voltage supplies. These overload pulses were likely due to slow protons which are a contaminant of the TRIUMF beamlines when positive particles are used. The M13 beam itself was created in the interaction between 500 MeV protons from the cyclotron and a beryllium target. The beam polarity was switched to negative for the data runs, and these beam-related overload events almost completely disappeared. All results presented in the following sections are for negative particles. For the purposes of determining MSGC characteristics, such as efficiency and spatial resolution, electrons were the most suitable particles. This was why the timing of the scintillator trigger was adjusted relative to the cyclotron RF signal to select electrons during most of the runs.

6.5.3 Efficiency

Using three 400 μm pitch MSGCs values of efficiency were determined and plotted as a function of the threshold in Figure 6.10. The efficiency was defined as being the number of events in which the central chamber recorded a signal

above this threshold divided by the total number of events where a clean track was indicated by data from the surrounding chambers. The data set used was that from the spatial resolution analysis (section 6.5.5) which included suppression of multiple track and shower events.

Also shown in Figure 6.10 are the pedestal and the rms noise level produced by the electronics, excluding the 18.5 MHz noise mentioned previously. For average operating voltages and reasonable pulse height cuts the detectors were running with efficiencies of up to 95%, which was excellent considering the speed of the amplifying electronics.

Figure 6.10: 400 μm pitch MSGC efficiency versus threshold.

6.5.4 Energy Resolution

Figure 6.11 shows the pulse-height distribution averaged over the individual anodes of a 400 μm pitch MSGC. The pulse height was defined as the maximum FADC value for the anode with the largest signal in an event. This variable was useful for determining the anode-to-anode signal uniformity and for comparison to the MSGC simulation (Chapter 7). The shape of the distribution at large values is due to saturation in the QPA02s.

Figure 6.11: Average pulse-height distribution.

6.5.5 Spatial Resolution

Using the configuration as shown in Figure 6.6 the spatial resolution of the 400 μm pitch Upilex MSGCs was determined with a 90-10 argon-isobutane gas mix and voltages of $V_{cath} = -680$ V and $V_{drift} = -2000$ V. The sixteen individual anodes in each of the three MSGCs was used, and spatial resolution was measured by finding the position-residual distribution in the central MSGC when all three detectors were nominally perpendicular to the beam. The residual was defined as the difference between the hit position in the central MSGC and the position predicted by a line passing through the hit positions in the two outer MSGCs.

Hit positions were measured using analog centroid finding. The position in a given detector was the centroid of all the hit (above threshold) anodes with the maximum pulse height on an anode used as a weight in the centroid determination. The spatial resolution was expected to be better than $400/\sqrt{12} = 116$ μm , which would be the value if only one anode in each chamber was hit, and could be compared to the results from the MSGC simulation.

There were five important factors which had to be considered during the analysis which, if not taken into account, would have resulted in an overestimation of

the MSGC spatial resolution:

- (i) electronic noise.
- (ii) detector misalignment.
- (iii) signal uniformity.
- (iv) multiple tracks and showers.
- (v) multiple scattering.

The first three factors are common in measurements of detector resolutions, and can be dealt with in a relatively straight-forward manner. The last two factors were more serious given the specific properties of the TRIUMF beam and the MSGC system, and required careful consideration.

As mentioned previously there was high frequency noise which, combined with the need to set a low threshold, was a problem in terms of the spatial resolution analysis. For each anode in a given event the FADC data were smoothed using a moving four-point average prior to applying a threshold cut. This operation was effectively a low-pass filter and served to improve the discrimination between noise-induced events and events corresponding to actual particle tracks.

Misalignments between the MSGC's, both translational and angular, were readily apparent in the data and most such misalignments were just as easily compensated. If one detector was shifted laterally with respect to the other two then the mean of the position-residual distribution would likewise shift from the ideal value of zero. If there was an angular misalignment between the detector planes then the residual mean would vary from one side of the system to the other. There was only one misalignment which could not be compensated, namely that of a relative angle between the directions in which the anodes of the MSGC's were pointing. Nominally all the anodes were vertical, however there was no independent way of measuring this using the test data. The mechanical precision of the chambers and their support structures was used to estimate the possible effect of this misalignment. Assuming that the vertical extent of the beam was defined by the 5 mm scintillators, a 10 mrad misalignment would contribute at most 25 μm to the width

of the position residual.

Using analog weighting to determine the hit position in a MSGC required that the channel-to-channel signal uniformity be known. Non-uniformity, if uncompensated, worsened the spatial resolution. There were three contributions to the signal on a given anode; the MSGC gain, the QPA02 gain, and the FADC response. The gain uniformity of the beam-test MSGCs had been measured using ^{55}Fe in the laboratory (see Chapter 5) and was better than $\pm 10\%$ in the central region of the MSGC prints. However, as discussed in section 6.1, there was some variation in the electronic gain of the QPA02 amplifiers. For the spatial resolution analysis the signal uniformity was measured by looking at the pulse-height distributions for each of the anodes. These had characteristic shapes similar to Figure 6.11, and were used to obtain the uniformity for the anodes in a given MSGC. Figure 6.12 shows this uniformity for one of the data runs, where the signals in the three MSGC have been normalized for the purposes of illustration. The channel-to-channel uniformity results for each MSGC were incorporated into the analog weighting.

Figure 6.12: Signal uniformity for three 400 μm pitch MSGCs.

Multiple Tracks and Showers

The characteristics of the TRIUMF M13 beam, combined with the way the MSGCs were read out, meant that it was critical that the spatial resolution analysis consider the effects of multiple tracks and showers. This analysis was made with

the assumption that there was a single charged particle passing through each of the three MSGCs, and that any signals on the anodes corresponded to its passage. However, as Figure 6.9b illustrated, there was clearly the potential for the data to include events where two or more particles had passed through the analyzed regions of the MSGCs. Recall that for each anode the data consisted of 40 FADC levels, digitized at 10 ns, which corresponded to 400 ns of real time. During this time nine electron buckets (43 ns spacing) had passed through the detectors, and the chance that there was a second particle was up to 5%.

In addition to the possibility of multiple tracks there was also the potential for events due to electromagnetic showers initiated in the upstream scintillator or in the MSGC chamber materials. The photons of these showers would distort the centroid finding and widen the position residual. For electrons at 130 MeV/c momentum there was more energy lost to bremsstrahlung than to ionization. Even for an isolated electron track high-energy photons would, on occasion, end up in the gas volume of a subsequent detector and distort its own track location. Since these long-range photons were emitted primarily in the direction of travel this effect would be most significant for events where the electron direction changed substantially due to scattering.

It was therefore important to find a way of reducing these effects. One useful variable in this regard was the time where the peak signal occurred. Figure 6.13 shows the time for the peak signal in three MSGCs, binned in the 10 ns FADC bins. The time represents the average time when more than one anode was hit.

Figure 6.13: Average time for peak signals in three MSGCs.

For most of the events the peak signals occurred in a 100 ns wide window, which corresponded to the drift time for the 90-10 argon-isobutane gas mix and the 4 mm MSGC gap. There were, however, some events with times outside this window. These events were likely to be predominantly those where multiple tracks, showers, or long-range photons had occurred.

Another way of ensuring that the data corresponded to a single, clean track was to look at the number of hit anodes in each MSGC and the spacing of these anodes. For nominal zero incident angle the expected maximum number of hit anodes was, on average, two or three. Even given some small angle, events with four or more hit anodes would more likely correspond to multiple tracks or a shower.

Figure 6.14: Cluster data for each of the three MSGC's.

As importantly there should not be a large number of unhit anodes within the hit cluster, i.e. no "gaps" in the hit segment. Figure 6.14 shows the data in terms of hit number and the number of gaps for the three MSGC's, referred to as the cluster data, for one of the runs. A cluster cut was defined such that only events where there were three or less anodes hit, and at most only one gap, were included in the position-residual analysis. A timing cut excluded events outside a 100 ns window in each MSGC. The results before and after this combined cut are shown in Figure 6.15. The success of these cuts in removing events in the wings of the position-residual distribution is evident.

Figure 6.15: Position residual in the central MSGC (a) before time and cluster cut (b) after time and cluster cut.

Multiple Scattering

The second important factor in the spatial-resolution analysis was multiple scattering. Measurements were conducted at two different detector separations, a , and b , in order to include the effects of multiple scattering. These configurations corresponded to a "close-packed chamber" situation, and the case where the MSGCs were positioned on their standard jig locations.

Figure 6.16: Position residuals for two detector separations.

The separations between consecutive chambers were $a = 5.1 \pm 0.2 \text{ cm}$ and $b = 13.7 \pm 0.2 \text{ cm}$. Figure 6.16 gives the position-residual distributions for two runs done at the indicated distances.

As described in Appendix B the multiple scattering which affected the position residual, for the geometry shown in Figure 6.6, was that due to material in the central MSGC. It was for this reason that the G-10 behind the active area was removed. The spatial resolution for the MSGCs was

$$\sigma_{space} = \sqrt{\frac{2}{3} \frac{b^2 \sigma_{\Delta xa}^2 - a^2 \sigma_{\Delta xb}^2}{b^2 - a^2}} \quad (6.2)$$

and the standard deviation of the multiple-scattering angle was

$$\sigma_{ms} = 2 \sqrt{\frac{\sigma_{\Delta xb}^2 - \sigma_{\Delta xa}^2}{b^2 - a^2}} \quad (6.3)$$

The average standard deviations of position-residual distributions were $\sigma_{\Delta xa} = 160 \pm 10 \mu\text{m}$ and $\sigma_{\Delta xb} = 330 \pm 15 \mu\text{m}$.

The resulting spatial resolution for the $400 \mu\text{m}$ pitch MSGC was $\sigma_{space} = 90 \pm 20 \mu\text{m}$. The calculated value of σ_{ms} was $4.5 \pm 0.3 \text{ mrad}$ which is somewhat smaller than the value of $5.7 \pm 0.4 \text{ mrad}$ determined from the radiation length. This difference may be due to the effect of the scintillator telescope, which favours small-angle scatter events over events where the scattering angle was large. Section 7.4.4 of the next chapter deals with the spatial resolution as predicted by the MSGC simulations.

6.5.6 Timing Resolution

Figure 6.17a shows the timing distribution, averaged over several individual anodes, from the $400 \mu\text{m}$ pitch argon-isobutane data. Time in this case is the time at which the signals crossed a fixed threshold. A narrow peak at small times is on top of a broader distribution whose width is consistent with the electron drift time over the full drift distance. Assuming that there was no electron attachment this indicated a drift velocity of $30 \pm 7 \mu\text{m/ns}$. The timing resolution was studied using the MSGC simulation and the results will be presented in section 7.4.3 of the next chapter.

Figure 6.17: Timing distributions for (a) argon-isobutane (b) CF₄-isobutane

The timing resolution of the detector was taken to be the width of the narrow peak which was $\sigma_{time} = 17 \pm 3$ ns for the argon-isobutane gas mix. Figure 6.17b shows the average timing distribution for 200 μm pitch anodes when CF₄-isobutane was used. The CF₄-isobutane was expected to be three or four times faster than argon-isobutane. The timing distribution supports this prediction, yielding a value of 130 ± 20 $\mu\text{m}/\text{ns}$ for the drift velocity. The timing resolution determined using the CF₄-isobutane distributions was smaller than the inherent resolution of the FADCs (10 ns). This improved timing resolution was consistent with the increased electron drift velocity.

6.5.7 Angle Effects and Drift Velocity Measurement

Figure 6.18 shows the passage of a particle through the central MSGC in the three-chamber configuration which has been rotated at an angle θ with respect to the beam and the other two chambers. Electrons deposited along the ionization path of the angled particle track had different distances to travel to the anodes and this fact was used to determine the drift velocity [79].

Figure 6.18: Angled track through a MSGC showing the time difference, Δt , and the histogram of Δt for a hit size of four anodes.

The experimental data for a given MSGC rotation angle were arranged according to the number of the hit anodes, referred to as the hit size. For each value of the hit size the differences in times to threshold for the anode pulses at either extreme of the hit segment were determined, $\Delta t = t_R - t_L$, and histogrammed. The inset of Figure 6.18 shows the distribution for a hit size of four anodes and an angle of 30° . The mean values of these distributions were found by applying Gaussian fits and, by making a simple geometrical conversion of hit size to equivalent path length difference for the specified angle, the plot shown in Figure 6.19 was obtained. The slope of the line corresponds to the electron drift velocity in the constant-field drift region. Because differential times were used the issues of the high-field avalanche region near the anodes and electron attachment were automatically removed from the analysis.

Figure 6.19: Distance versus time obtained from the 15° and 30° MSGC angled-track data.

The drift velocity of the 90-10 argon-isobutane mix at the MSGC drift field of 4 kV/cm was determined to be $36 \pm 2 \mu\text{m/ns}$. This is consistent with the value of $34 \pm 3 \mu\text{m/ns}$ obtained from simulations, as discussed in Chapter 7, and the $30 \pm 7 \mu\text{m/ns}$ indicated by the overall timing distributions. There was no measurable electron attachment in the argon-isobutane gas mix.

Chapter 7

Simulation

Simulations of MSGCs are valuable in understanding experimental results and in predicting performance in future applications. Two detailed MSGC simulations have been made using the geometries given in Table 7.1. The first was of a 400 μm

	TRIUMF MSGC	ATLAS MSGC
pitch (μm)	400	200
substrate	Upilex	D-263 glass
thickness (μm)	125	300
R_s ($\Omega/\square$)	10^{14}	10^{14}
anode width (μm)	20	10
cathode width (μm)	88	70
drift gap (mm)	4.0	2.5
gas mixture	90-10 Ar- $i\text{C}_4\text{H}_{10}$	50-50 Ar-DME

Table 7.1: Geometry of the simulated MSGCs.

pitch MSGC, fabricated on ion-implanted Upilex, with the same gas mixture and operating voltages that were used at the TRIUMF beam test. The results of this simulation were compared to the experimental findings presented in the previous chapter. The second simulation was of a 200 μm pitch MSGC, built on Desag D-263 glass, and proposed for use in the ATLAS inner tracker. The results were used to predict the MSGC's operating voltages and investigate different ATLAS read out schemes. The two different MSGC simulations will be described in sections 7.4 and 7.5. There are many programs which simulate the operation of MWPCs,

drift chambers, and Time-Projection Chambers (TPCs). GARFIELD [80] is one such program which has been used in various applications [43] including the modelling of an early glass MSGC [38]. The MSGC substrate, a resistive dielectric, must be included in any simulation and this was one factor which motivated the development of programs specifically designed for a MSGC geometry. Table 7.2

program	author	institution	ref.	description
MSFIELD	J. Gaudaen	CERN	[30]	mainly E-field
MSGC	J. Schmitz	NIKHEF	[81] [82]	parametric
MSGCSIM	S. Biagi	U. Liverpool	[83]	detailed
MSGC/MGC	M. Spezziga	INFN	[23]	detailed, flux effects

Table 7.2: MSGC simulation programs.

lists four MSGC simulation programs along with their authors and institutions. These programs, as well as ones used within other MSGC groups, vary in the detail to which the ionization, drift, diffusion, avalanche, and signal formation are modelled. Simpler, quicker programs tend to use extensive parameterization of some or all of these different processes. The results presented in this chapter were obtained using a modified and extended version of MSGCSIM which is one of the most detailed programs. In order to obtain the inputs for MSGCSIM a number of other programs, including MSFIELD, were used and these programs will be discussed prior to the description of MSGCSIM. Figure 7.1 shows the relationship between the various programs used to generate the TRIUMF and ATLAS MSGC simulation results.

Figure 7.1: Block diagram showing programs used in the simulation.

Unless explicitly stated otherwise all programs were run on the Carleton Physics Department-CRPP computing facility which is an integrated network of VAX-VMS and UNIX workstations. The UNIX system included a farm of eight DEC 5240 processors, running at 40 MHz, on which most of the simulations were performed.

7.1 Electrostatic Modelling

The starting point of a detailed MSGC simulation is the calculation of an electric field map for the particular geometry, substrate, and electrode voltages. This information is subsequently used to drift and avalanche the electrons, track the motion of the avalanche electrons and ions, and produce simulated output signals. Two different electrostatic modelling packages were used for the MSGC simulation, (i) a modified version of MSFIELD and (ii) ELECTRO.

7.1.1 MSFIELD

MSFIELD was specifically designed to perform electrostatic field calculations in MSGCs. It was developed to study detectors fabricated on glass, Tedlar, and untreated Kapton and has subsequently been used by the group at CERN to optimize MSGC geometry [84]. MSFIELD is based on a multigrid method which was unfortunately not optimized for the sub-micron thick, surface-modified layers of ion-implanted Upilex MSGCs. However the program was useful in early research with the Tedlar MSGCs whose experimental results were presented in the previous two chapters. MSFIELD also provided insight into the effect of “keystoning” electrodes for the ITD detector, as described in Chapter 2. MSFIELD includes a parameterized Townsend coefficient for P-10 gas (90% argon, 10% methane) and calculates the gas gain for the given MSGC geometry and operating voltages. The program also predicts voltage configurations which minimize surface charging and thus increase the rate capability of MSGCs built on high-resistivity substrates such as Tedlar or untreated Upilex. Most importantly, in the context of this thesis, MSFIELD was used initially to generate the voltage maps required by the

MSGCSIM program. This task was later carried out using ELECTRO, which was more suited to ion-implanted Upilex calculations.

7.1.2 ELECTRO

ELECTRO 2D, Version 3.7, was purchased from Integrated Engineering Systems (IES) of Winnipeg, Canada, and was run on a 50 MHz 80486 personal computer. ELECTRO is an electrostatic modelling program which uses a boundary-element method and has been used for field calculations in MSGCs and MGCs by the group at INFN [22] [28]. It was convenient to use, particularly in the entry of the MSGC geometry which was done graphically via a mouse. Once the geometry was entered the boundary conditions, voltages, and material characteristics were defined. The electrostatic variables, namely the voltage and electric field components were calculated and displayed. The voltages on a user-specified grid were also output to file and used in MSGCSIM. These voltage maps corresponded to the MSGCSIM cell geometry as described in section 7.3.1.

Figure 7.2: Contour map of voltages above MSGC surface.

Figure 7.2 shows the voltage contours, spaced every 75 volts, for a 400 μm pitch MSGC fabricated on ion-implanted Upilex in a high-field region extending 200 μm into the gas volume. The anode, at the center of the surface, is grounded while the cathodes are at -680 V.

7.2 Gas Data Calculation-MAGBOLTZ

MSGC simulation requires detailed electron-transport information for high electric fields, and this data is often not available. There are, however, numerical simulations which utilize cross-sections to predict the field-dependent electron-transport parameters. The theory behind one of these programs, MAGBOLTZ, was presented in Chapter 3, and its results will now be described.

MAGBOLTZ [51] calculates a variety of parameters for gas mixes comprised of up to four different gases to a numerical accuracy of 0.1%. The output values have been found to agree to within 1% and 5% of experimental data for gas mixes where such data were available. An uncertainty of 10% was assumed for all MAGBOLTZ results reported here to reflect uncertainties in gas pressure, temperature, and mix composition. MAGBOLTZ was used to create the data for the eight gas mixes which were already included in the MSGCSIM program. One of these gas mixes was the 50-50 argon-DME mix which was used in the ATLAS MSGC simulation. However argon-isobutane gas mixes used at the TRIUMF beam test, the third CERN beam test, and in the laboratory, were not included in the existing MSGCSIM gas data. MAGBOLTZ, Version 2.2, was used to generate the required gas parameters and the remainder of this section will discuss these results, concentrating on the TRIUMF 90-10 argon-isobutane mix.

The data obtained from MAGBOLTZ were the electron drift velocity, electron diffusion coefficients, and Townsend gain factor at electric field values ranging from 0.1 to 8000 kV/cm. For all calculations the gas pressure was set at one atmosphere (760 torr), the gas temperature was 20°C, and there was zero magnetic field. Figure 7.3 shows the electron drift velocity, v_d , as a function of the percentage of isobutane in the mix for an electric field, E , of 4 kV/cm, which was the field in the drift region of the TRIUMF beam test MSGCs. Figure 7.4a gives the drift velocity for a 90-10 mix versus the electric field. There was a good fit between the calculated drift velocity and experimental results at the low electric fields for which such data is available. The experimental points are also shown in Figure 7.4a.

Figure 7.3: Electron drift velocity versus isobutane fraction.

Figure 7.4: Electron-transport parameters for a 90-10 argon-isobutane gas mix (a) drift velocity (b) diffusion coefficients.

The longitudinal and transverse electron diffusion coefficients, D_{long} and D_{trans} , are shown in Figure 7.4b. In the constant-field drift region of a MSGC this diffusion leads to spatial electron distributions characterized by

$$\sigma_{long} = \sqrt{\frac{2x D_{long}}{v_d}} \quad \text{and} \quad \sigma_{trans} = \sqrt{\frac{2x D_{trans}}{v_d}} \quad (7.1)$$

where x is the distance travelled by the electrons. At a value of 4 kV/cm the transverse diffusion is $\sigma_{trans} = 120 \mu\text{m}/\sqrt{\text{mm}}$. The maximum transverse diffusion

is $\sigma_{trans}^{max} = 240 \mu\text{m}$ for the 4 mm gap of a TRIUMF beam test MSGC, while the average transverse diffusion is $\sigma_{trans} = 196 \mu\text{m}$. The 90-10 argon-isobutane gas data from MAGBOLTZ were incorporated into MSGCSIM so that this mix could be used by the program.

7.3 Detailed MSGC Simulation-MSGCSIM

MSGCSIM is a detailed simulation program developed by Steve Biagi at Liverpool University to study MSGCs fabricated on glass and quartz substrates. A modified and extended version of MSGCSIM 2.6.2 was used for the TRIUMF and ATLAS simulations. The changes and additions will be discussed later, but the general operation of the program will first be described. Note that throughout this discussion anode read-out will be assumed, although the program is capable of providing cathode, backplane, or drift electrode read-out.

MSGCSIM is controlled by an input file which is read in at the start of program execution. This file is used to select the various parameters used within MSGCSIM including the choice of gas mix and the nature and type of ionizing radiation. The program has two distinct stages:

- (1) calculation of current arrays (section 7.3.2),
- (2) simulation of ionization events (section 7.3.3).

Stage (1) is run once for each MSGC geometry and gas mix, and the program requires voltage maps for these calculations. As implemented locally these voltage maps were generated using ELECTRO. In stage (2) ionizing radiation is passed through the MSGC, and the results of the previous calculation used to build up the anode signals on an event-by-event basis.

Table 7.3 summarizes the parameters used in the two simulations. The time and memory requirements are for the UNIX farm. In the case of the TRIUMF simulation the stage (1) calculation, where the current arrays are filled, required 6000 seconds (100 minutes), of central processing unit (CPU) time and ten MIPs were simulated in four CPU seconds. 100,000 MIPs required six hours of CPU.

	TRIUMF MSGC	ATLAS MSGC
high-field lattice	201×101	201×101
spacing (μm)	2	1
electron steps (ns)	0.0125	0.0125
ion steps (ns)	0.1	0.1
drift lattice	21×191	21×241
spacing (μm)	20	10
electron steps (ns)	0.125	0.125
ion steps (ns)	1	1
time bins	$150 \times 1 \text{ ns}$	$100 \times 1 \text{ ns}$
memory required (MB)	48	36
array fill (CPU s)	6000	3100
10 MIP events (CPU s)	4	3

Table 7.3: MSGCSIM parameters for the simulations.

7.3.1 Geometry

The basis for MSGCSIM is a “cell” which, as shown in Figure 7.5, consists of the gas region enclosed by the drift electrode, the MSGC substrate surface, and lines passing through the centers of the cathodes. The anode is located at the center of this cell. The program uses 20 such adjacent cells, i.e. provides information for the read-out of 20 consecutive anodes. Each cell is subdivided into two distinct regions which correspond to grids of points in the gas volume. The “high-field” region is a lattice of 201 points by 101 points above the MSGC surface. The “drift” region is a lattice of 21 (maximum) points by 501 (maximum) points covering the remainder of the gas volume. The scaling in the high-field region is determined by the actual pitch of the MSGC being modelled, while the size of the lattice in the drift region is adapted to the particular MSGC geometry by using an appropriate number of points. Each point on the lattices is used as a starting point of an initial electron and an initial ion, as described in the next section.

Figure 7.5: Definition of MSGCSIM cell.

7.3.2 Stage (1): Calculation of Current Arrays

Initial electrons and ions, starting at each of the lattice points, were drifted to the MSGC electrodes, and in the case of electrons, avalanched using the gas data and the voltage maps. The currents induced on the anode due to this motion were determined using Ramo's theorem, as discussed in Chapter 3, and four different arrays were filled. The two electron current arrays consisted of the charge induced per time bin (1 ns) due to the arrival of the avalanche electrons at the anode for electron starting points in the drift lattice and high-field lattice respectively. The two ion current arrays consisted of the induced charges per time bin on the anode due to an ion starting at each lattice point and were of the same size as the respective electron arrays. Most of the induced charge is due to the motion of the ions away from the anode in what corresponds to the "avalanche" region. The integration time steps used for electron motion in the drift lattice and the high-field lattice were 0.125 ns and 0.0125 ns respectively. For ion motion the steps were 1 ns and 0.1 ns.

The current arrays were stored to file and so the detailed electron and ion transport calculations were performed only once for a given gas mix and MSGC voltage configuration. The penalty for this reduction in computation time was the need to manipulate these large arrays, which resulted in the use of considerable memory.

7.3.3 Stage (2): Simulation of Ionization Events

After the current arrays had been calculated the program mode was changed and the simulation of actual ionizing events was performed. In this stage minimum-ionizing particles (MIPs) or X-rays were passed through the MSGC and, for each event, the initial positions of the ionization electrons and ions were determined. The type, angle, and position of the ionizing radiation could be selected.

Figure 7.6a shows the initial ionization electrons created by the passage of a single MIP directed perpendicular to the detector plane and passing through an anode. Figure 7.6b gives the ionization electron cloud created by a 5.9 keV ^{55}Fe X-ray which was also directed towards an anode. The figure illustrates the clear difference between the ionization induced by a MIP and that from an X-ray, as had been discussed in Chapter 3.

Figure 7.6: Initial electrons for (a) MIP and (b) ^{55}Fe X-ray.

Using the current arrays previously calculated the currents for the electrons starting from the corresponding closest lattice points were summed to give an overall

electron current and ion current for each event. For the same single MIP event shown in Figure 7.6a the electron and ion currents induced on the central anode are presented in Figure 7.7.

Figure 7.7: Signals induced on the central anode for a MIP (a) electron-induced current (b) ion-induced current.

7.3.4 Modifications and Extensions

MSGCSIM was originally designed to use voltage maps created by MAXWELL 2D Field Simulator [85], a commercial finite-element program from Ansoft. Local modifications were required to use information from MSFIELD or ELECTRO instead, and to minimize program size and memory requirements while at the same time accurately reflecting the TRIUMF and ATLAS MSGC geometries. The output of MSGCSIM was modified so that the many histograms created during program execution were written directly to a *hbook* file for subsequent display. These histograms included the results of new analysis routines incorporated within the modified program itself.

Most significantly the signals on the anodes were shaped in MSGCSIM as they would be by a QPA02 amplifier. MSGCSIM had no capability to do such shaping which, as will be described later in this Chapter, is a critical factor in determining how a MSGC will ultimately perform. The specific changes to MSGCSIM made

for the TRIUMF and ATLAS simulations will be described in greater detail in the following sections.

7.4 TRIUMF Simulation

A 400 μm pitch MSGC, such as used at the TRIUMF beam test, was simulated and the results compared to the actual experimental data. The gas mix was 90-10 argon-isobutane whose characteristics were obtained from MAGBOLTZ as described previously in section 7.2. The drift gap was 4.0 mm and the voltages were $V_{cath} = -680$ V, $V_{back} = -700$ V, $V_{drift} = -2000$ V.

7.4.1 QPA02 Shaping

One of the most important extensions made to MSGCSIM was that the anode signals were shaped as if they were read-out by the fast QPA02 amplifiers used at the beam tests. The electron and ion currents induced on each anode, such as shown in Figure 7.7, were first summed as given in Figure 7.8a where the charge is now expressed in fC. This signal was then shaped by convolving it with the measured impulse response from a QPA02, with a gain of 10 mV/fC, to produce the result shown in Figure 7.8b. This convolution was done in the frequency domain using a Fast Fourier Transform (FFT) [86] in order to speed program execution. These QPA02-shaped signals were then used in further analysis routines added to MSGCSIM.

Figure 7.8: MIP anode signal (a) before shaping (b) after shaping.

7.4.2 Signal Magnitude and Energy Deposition

100,000 randomly-located MIPs, all perpendicular to the MSGC, were simulated and the QPA02 signal heights were histogrammed. Figure 7.9a shows the signal-height distribution for all the anodes while Figure 7.9b gives the distribution for the maximum signal height. This maximum signal height was usually on the anode closest to the particle track.

Figure 7.9: Pulse-height distributions (a) all signals (b) maximum signal.

The “Landau” shape of the maximum pulse height is evident. However, when all anodes are included the distribution is dominated by small signals. These

correspond primarily to diffusion of some of the initial ionization electrons from the cell through which the particle passed into adjacent cells. There is also a contribution due to large-cluster events (δ -rays) which extend laterally for some distance from the actual track. These results suggested that the maximum pulse height would be a convenient parameter to use in the analysis of the TRIUMF test beam data, which indeed was done as described in Chapter 6. Figure 7.10 shows the total avalanche charge collected by all the anodes, and this is the closest to a true Landau energy distribution as given in Figure 3.3 of Chapter 3.

Figure 7.10: Avalanche charge distribution.

7.4.3 Timing Resolution

There were three effects, discussed below, which contributed to the 90-10 argon-isobutane timing distribution shape as shown in section 6.5.6 of the previous chapter. Recall that this experimental distribution had a narrow peak ($\sigma_{time} = 17 \pm 3$ ns) on a wide base which corresponded to the full drift time. For the 4.0 mm TRIUMF drift gap, and a MAGBOLTZ-predicted electron drift velocity of 34 ± 3 $\mu\text{m}/\text{ns}$, this drift time was 120 ns. This was essentially the measured width of the timing distribution at its base. The TRIUMF MSGC simulation was

very useful in understanding these effects, particularly that of a fast shaping time combined with a high threshold.

(1) Angled Tracks

The first and most obvious contribution to the wide base was the possibility of angled tracks. For a 400 μm pitch MSGC and a 4 mm drift gap any particle which was incident at an angle greater than 5.7° always crossed more than one MSGC cell. Particles with smaller incident angles still had a probability of physically passing through a portion of two MSGC cells given that the tracks were randomly located. The arrival times of the electrons in the cells depended on the drift distances, and for angled tracks these ranged from zero up to the entire drift gap.

(2) Diffusion and δ -rays

Diffusion of primary electrons contributed to the base of the distribution since for MIPs these electrons are initially deposited all along the particle track. When electrons undergo transverse diffusion into adjacent cells their arrival times can consequently span the entire drift gap distance. Similarly to electron diffusion, δ -rays produce signals in adjacent anodes whose arrival times span the entire drift time, and they are another mechanism of transverse electron spread in a MSGC. Figure 7.11a shows the simulated timing distribution for the anode whose cell contained the particle track, while 7.11b gives the distribution for all the anodes. All MIPs were at zero incident angle. The figure illustrates the effect of transverse electron spread due to diffusion and δ -rays. Note that the peak in the distribution of 7.11a is present in 7.11b but is somewhat masked by the adjacent-anode events.

Figure 7.11: Timing for zero-angled MIPs (a) nearest anode (b) all anodes.

(3) Fast shaping time and high threshold

This final effect was the most significant in terms of understanding the experimental timing distributions, and was also critical in the drift velocity measurement (section 6.5.7). The fundamental factor to consider is the relationship between the speed of the read-out electronics and the total drift time in the MSGC.

The response time of the QPA02 (30 ns) was significantly shorter than the drift time (120 ns) for the argon-isobutane gas mix used at TRIUMF. Only a quarter of the drift gap falls within the QPA02 response time. The resulting effects would not be evident if the trigger threshold were set at a single electron, since in this case the arrival of the first electron would be detected. Figure 7.12 shows the simulated timing distribution for zero-angle MIPs when the threshold was set to that corresponding to a single electron. This distribution just replicates the shape of the impulse response of the QPA02 amplifier.

Figure 7.12: Nearest-anode timing with single-electron threshold.

However, at higher thresholds, corresponding to those needed at the beam test to remove electronic noise, the mismatch of the read-out speed to the MSGC' gas and geometry has a dramatic effect.

Figure 7.13: Nearest-anode timing (a) 10 mV threshold (b) 30 mV threshold.

Figure 7.13 gives the timing distributions for the nearest anode with two different thresholds, 10 mV and 30 mV. Again note that all the MIPs were at zero incident angle with respect to the MSGC. The contribution from the wide "drift-time" base increases relative to the initial QPA02-like peak because the statistics of initial

ionization become more important. A given threshold was exceeded only when a length of a particle's ionization track, corresponding to the QPA02 response time, contributed the equivalent required amount of charge.

Referring to Figure 7.8b, there were two distinct peaks in the simulated QPA02 signal from this particular MIP event. For clarity the peaks in a read-out signal will be referred to as *peaks*. The first, and largest *peak* was 37 mV at a time of 35 ns, with a second major *peak* of 27 mV at 110 ns. These *peaks* were associated with the clumps of primary electrons which produced the current as in Figure 7.8a, and which were located as shown in Figure 7.6a. The number, magnitude, and time at which *peaks* in the QPA02 signal occurred were "random" because this was governed by the primary deposition statistics, both in terms of location and cluster size, and the avalanche fluctuations. The times at which a given threshold was crossed had a possible range corresponding to the total drift time.

It is useful to illustrate this by returning to a numerical example. Consider Figure 7.8b and a high threshold, say 30 mV. The threshold was crossed at 30 ns and this would be the data point contributed to the timing-distribution histogram. Now suppose that the heights of the *peaks* were simply reversed, such that the first *peak* was 27 mV at 35 ns, while the second *peak* was 37 mV at 110 ns. This event was just as likely as the one shown in Figure 7.8b, however now the threshold of 30 mV was crossed at 105 ns. The effect of a relatively high threshold, combined with the multi-*peak* nature of the QPA02 signals, was to produce a timing distribution which had a width equivalent to the total drift time.

Useful information could be extracted from the different QPA02 *peaks* since these *peaks* corresponded to bunches of ionization electrons located at different positions along the particle track (Figure 7.6a and Figure 7.8 again). If one measured the timing of individual *peaks*, and knew their spatial relationship, then the electron drift velocity could be determined by looking at differences in the times between the *peaks*. How does one separate the individual *peaks*? By angling the particle track such that the ionization from different locations along the track goes

to different anodes. This is exactly what had been done during the TRIUMF beam test as described in section 6.5.7 of the previous chapter.

Angled tracks and clusters Viewing the angled-track measurements in terms of this discussion also provided an insight into the choice of threshold used in the analysis of the beam-test results. The optimum threshold corresponded to the situation where the ionization in the segment of track matched the response time of the QPA02. In other words the average amount of ionization in the portion of track which was within one QPA02 *peak* should be a reasonable value to use. 30 ns was equivalent to 1 mm of track length and an average of 10.5 ionization electrons (in 3.5 different clusters) were deposited in this distance. At a gas gain of 1000, and a QPA02 charge gain of 10 mV/fC, the average signal produced by a MIP in 1 mm of gas was 16.5 mV. The value found to yield the best statistics during the analysis of the TRIUMF angled-track data was 15 mV. The close comparison between these two thresholds was another indication that the fast shaping time and high-threshold effect was critical in understanding the experimental results.

Result of FADC binning

Figure 7.14 shows the simulated timing distribution when the effect of the 100 MHz FADCs were included. This distribution was obtained by including a random time uncertainty of up to 10 ns for each simulated event to replicate the beam test conditions. Recall that the FADC sampling clock was asynchronous with the scintillator trigger. The width of the initial narrow peak is again taken to be the timing resolution and the value from the simulation is $\sigma_{time} = 15 \pm 1$ ns.

Figure 7.14: Timing resolution with FADC binning uncertainty.

7.4.4 Spatial Resolution

The TRIUMF MSGC simulation was also used to generate results in terms of the spatial resolution of the 400 μm pitch MSGCs for zero-angled MIPs. A digital resolution was calculated by histogramming the residual between the actual track position and the position as determined by finding the geometrical center of all hit anodes. For example if two adjacent anodes were hit then the digital position was just at the boundary between the two cells. A hit anode was one where the simulated QPA02 signal exceeded a specified threshold. Analog resolutions were also determined using simple centroid finding. In this case the analog position was the position determined when either the maximum signal amplitude or the integrated signal (referred to here as the “charge”) in each hit anode was used for weighting. For instance if two adjacent anodes had maximum signals of 50 mV and 25 mV then the analog amplitude position was a third of an anode pitch away from the anode with the bigger signal.

The digital and analog spatial resolutions were calculated as a function of the threshold and are shown in Figure 7.15.

Figure 7.15: Spatial resolutions for digital and analog centroid finding.

The analog resolution was only better than the digital resolution for thresholds below about 30 mV, and above this threshold both were essentially 116 μm . This is the resolution expected for the case when only one anode is hit, $400/\sqrt{12} = 116$. Figure 7.16 shows that beyond 30 mV most events consist of only one hit anode, and there are several anodes hit only below 20 mV.

Figure 7.16: Fraction of multi-hit events.

The resolution is dependent on the amount of transverse diffusion in the gas relative to the anode pitch. Other MSGC simulations have shown that the digital spatial

resolution is optimum for $0.22 < f < 0.28$ and the analog spatial resolution is optimum at $0.35 < f < 0.55$ where $f = \sigma_{trans}^{max} / \text{pitch}$ (refer to section 7.2). The TRIUMF MSGC had $f = 0.6$, which was outside the optimal range in both cases.

7.4.5 Efficiency

The simulation was used to determine the efficiency of the $400 \mu\text{m}$ pitch MSGC as a function of the threshold and the results are given in Figure 7.17. This simulated efficiency could be compared to the experimental results presented in section 6.5.3 of the previous chapter.

Figure 7.17: Simulated efficiency.

7.5 ATLAS Simulation

A $200 \mu\text{m}$ pitch MSGC, which will be used at ATLAS, was simulated to determine suitable operating voltages and to begin local investigations of the relative merits of different read-out schemes. The gas mix was 50-50 argon-DME and, as described previously in Table 7.1, the drift gap was 2.5 mm. The information in the left-hand column of Table 7.4 summarizes the requirements for ATLAS [27], while the right-hand column presents the results of the simulation in terms of the

	ATLAS Specification	Simulation Result
cathode voltage (V)	n.s.	- 580
drift voltage (V)	n.s.	1900
drift field (kV/cm)	n.s.	6
drift velocity ($\mu\text{m}/\text{ns}$)	≥ 50	52
avalanche gain	≈ 3000	3500
gain in 20 ns	≈ 1500	1300

Table 7.4: ATLAS requirements and results of the simulation. MSGC voltages and gas gains. With $V_{cath} = -580$ V and $V_{drift} = 1900$ V all the specifications are met. These voltages appear to be consistent with experimental results obtained using other argon-DME gas ratios in 200 μm pitch Carleton CRPP detectors.

The signals on the anodes, such as that shown in Figure 7.18, were saved to file to be used in a separate shaping and analysis routine. This program used simple descriptions of amplifiers to shape the signals, add noise, and implement three different ATLAS readout schemes [87]. However only preliminary results were obtained prior to the focus of the Carleton-CRPP group being re-directed elsewhere, namely away from the ATLAS MSGC to the ATLAS liquid-argon calorimeter.

Figure 7.18: Anode signal for a MIP in the ATLAS MSGC.

Chapter 8

Discussion and Conclusions

This thesis has presented the results of four years of research into plastic gas microstrip detectors. These devices were fabricated through collaboration with industry and MSGC prints of good quality with the desired surface resistance were obtained. The choice of Tedlar and Upilex as the substrate material required the development of new processes which will be needed in any large-scale production of MSGCs for high-energy physics or medical applications. The research has provided significant insight into the fundamental physics of MSGC operation, and the dissemination of this knowledge was particularly important given the immaturity of the field.

In retrospect the work on plastic substrates has had a distinctly double-sided nature. On one hand, groups working with other substrates, especially glasses, have produced high-quality, large-area detectors with less difficulty and there have been considerably more experimental data collected with their MSGCs. On the other hand these groups are only now addressing the substrate thickness and resistivity issues that have been integral to plastic MSGC research from the very beginning. Applications where radiation length considerations are dominant will push the continued development of plastic MSGCs, and the insights gained so far will also be useful in thin glass detectors.

The remainder of this final chapter will summarize and discuss the results of the plastic MSGC research presented in previous chapters. Recommendations will be made as to the direction of future studies.

8.1 Summary of Results

The fundamental difference between the Tedlar and the ion-implanted Upilex MSGCs was that the former relied on bulk conduction in the substrate while the latter used surface conduction. Tedlar MSGCs had gain which was dependent on the backplane voltage while the gain of ion-implanted Upilex MSGCs was independent of the backplane voltage. For a given gas mix and geometry the relative performance of the two types of plastic MSGCs depended entirely on the incident fluxes. At low fluxes, where charging was minimal, the Tedlar MSGCs had higher gain than the ion-implanted Upilex MSGCs because the backplane voltage could be used to increase the average anode surface field. At high fluxes the Upilex MSGCs were superior since, unlike the Tedlar MSGCs, there was no fall in gain due to charging.

The experimental and simulation results for a 400 μm pitch ion-implanted Upilex MSGC were in very good agreement, as shown in Table 8.1. These results were for a 90-10 argon-isobutane gas mix, operating voltages of $V_{\text{cath}} = -680$ V, $V_{\text{back}} = -700$ V, $V_{\text{drift}} = -2000$ V, and a 4 mm drift gap. The drift field was 4 kV/cm. Several of the interesting results from the last beam test were due to the

	experiment	simulation
σ_{space} (μm)	90 ± 20	85 ± 2
σ_{time} (ns)	17 ± 3	15 ± 1
efficiency (%)	93 ± 1	90
v_{drift} ($\mu\text{m}/\text{ns}$)	36 ± 2	34 ± 3

Table 8.1: Summary of results for 400 μm pitch Upilex MSGC. combination of the fast QPA02 read-out electronics and the relatively slow argon-isobutane gas mix. One benefit of this combination was that it was possible to measure the electron drift velocity using a new method which looked at differential times for angled ionizing tracks. The experimental value obtained, 36 ± 2 $\mu\text{m}/\text{ns}$, was entirely consistent with the 34 ± 3 $\mu\text{m}/\text{ns}$ predicted by the electron-transport program MAGBOLTZ.

Extensive data from MAGBOLTZ were used in the full MSGC simulation. The fundamental detector processes were clearly being modelled quite accurately in the extended and modified version of MSGCSIM. Using the detailed MSGC simulation a set of operating voltages was obtained for the 200 μm pitch MSGCs which will be used in the ATLAS detector. Preliminary results from the ATLAS MSGC simulation were used in the study of different readout schemes.

8.2 Other MSGCs

The experimental and simulation results for the plastic MSGCs can be compared to those for devices fabricated on other substrates. It is useful to look at a few such results which are presented in Table 8.2. The same sorts of experimental measurements were made using these detectors as were made with the plastic MSGCs. Direct comparison is often difficult because the MSGC electrode geometry, substrate thickness, resistivity, operating voltages, and gas mixture vary widely. However the general trends suggested in other data are informative in putting the plastic MSGC results into context. Like the plastic MSGCs these detectors have ^{55}Fe energy resolutions of about 20% and measured spatial resolutions corresponding to a quarter of the pitch.

Substrate	Pitch (μm)	Gas Mix	^{55}Fe Energy Resolution	Spatial Resolution (μm)
glass [38]	200	Ar-CO ₂	18%	50
silicon[28]	200	Ar-DME	18%	50
D-263 glass [82]	200	DME-CO ₂		54

Table 8.2: Summary of results from other MSGCs.

8.3 Recommendations

Based on the results presented in this thesis, and on other MSGC work that is currently ongoing, a number of recommendations can be made. The research has been dominated by high-energy physics applications, but it appears that medical imaging and other uses will increasingly become the focus.

There are some questions which have yet to be answered in terms of using plastic MSGCs in any application. How stable will the surface resistivity of the plastic substrates be over long times? This is critically important because the high-rate performance of MSGCs relies to a great extent on the tailored characteristics of the substrate surface. Will the surface modifications such as ion-implantation or thin-layer coating change over time due to ageing or other effects? Accelerated ageing tests, some of which have already been performed, may not provide definitive results.

Another topic which is of concern is that of MSGC damage mechanisms. Results to date seem to suggest that nickel-nickel oxide coated polyimide MSGCs suffer much less damage than their ion-implanted counterparts. Evidence supports ion-induced electron emission from the cathode as being a likely mechanism, but a systematic study has yet to be done. Such research requires a large number of MSGC prints with uniform and well-defined quality and this has only recently become a possibility.

Simulations of MSGCs can become ever more sophisticated and include flux effects and even more detailed avalanche modelling. However the utility of generic detailed MSGC simulations is questionable once they begin to require extensive CPU time. There are really only two parameters which must be known if one is to have a feeling for how a given MSGC will perform in terms of spatial resolution. These are the electron drift velocity and the transverse diffusion coefficient. Combined with the MSGC pitch and drift gap it should be possible to predict the optimal resolution in a given application. In this context it is important that these variables be tracked as additional MSGC experiments are performed, es

pecially with new gas mixes or different gas pressures. A fast program such as MAGBOLTZ, with tested gas cross-section data, will be useful for this purpose.

Finally, and perhaps most importantly, is the question of the applications for plastic MSGCs, and MSGCs in general. Large high-energy physics projects such as ATLAS have provided the resources for much of the research to date, including the funding. With the general swing from basic to applied research a new technology like MSGCs is in a delicate position. The potential rewards for investment are great but so are the risks. Much effort is directed at trying to interest industry, government, and disciplines outside of high-energy physics, in MSGCs and their applications. This is certainly important since much research is still to be done which will only be possible with continued support.

Appendix A

Rapidity and Pseudorapidity

Consider Figure A.1 which shows a particle which has been produced in the interaction between two high-energy particles (7 GeV protons at the LHC).

Figure A.1: Collision between two high-energy protons.

With the beam axis being the z axis the rapidity of the particle, y , is related to its energy, E , and z -momentum, p_z , by

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) = \tanh^{-1} \left(\frac{p_z}{E} \right) \quad (\text{A.1})$$

Rapidity is a useful parameter since particle production is essentially uniform in terms of rapidity, and it allows one to scale up particle cross-sections from the Fermilab TeVatron (1 TeV) to the SSC (20 TeV) and LHC (7 TeV).

Pseudorapidity, η , is related to the angle of the particle's path with respect to the beam axis, θ , via the relationship

$$\eta = -\ln \tan \left(\frac{\theta}{2} \right) = \tanh^{-1} (\cos \theta) \quad (\text{A.2})$$

For very high-momentum particles this is a good approximation to the rapidity.

Appendix B

Residuals and Spatial Resolution

The spatial resolution of the MSGCs at the TRIUMF beam test was determined using relationships whose derivations are provided here. Figure B.1 shows three detection planes, spaced a distance, d , apart. In the TRIUMF beam test each plane was a $400\ \mu\text{m}$ pitch plastic MSGC.

Figure B.1: Passage of a charged particle through three equally-spaced detection planes (a) no multiple scattering (b) multiple scattering.

Figure B.1a gives the ideal case where there is no multiple scattering, and the charged particle travels in a straight line through the three detection planes. Figure B.1b represents a more realistic situation which includes multiple scattering. For the sake of illustration the angles of scattering have been greatly exaggerated. The problem is to determine the spatial resolution of the MSGCs, and the two cases will be considered in turn.

(a) **No Multiple Scattering** Let x_1 , x_2 , and x_3 be the positions determined by using the data in the three detectors. The separation between the hit position in the central MSGC, and the predicted position using the hit positions in the outer MSGCs, the residual, is

$$\Delta x = \frac{1}{2} (x_1 + x_3) - x_2 \quad (\text{B.1})$$

If the positions are normally distributed then

$$\sigma_{\Delta x}^2 = \frac{1}{4} \sigma_{x_1}^2 + \frac{1}{4} \sigma_{x_3}^2 + \sigma_{x_2}^2 \quad (\text{B.2})$$

Assuming that the spatial resolutions of the MSGCs are the same,

$\sigma_{x_1} = \sigma_{x_2} = \sigma_{x_3} = \sigma_{\text{space}}$, then $\sigma_{\Delta x}^2 = \frac{3}{2} \sigma_{\text{space}}^2$, and the spatial resolution is

$$\sigma_{\text{space}} = \sqrt{\frac{2}{3}} \sigma_{\Delta x} \quad (\text{B.3})$$

(a) **Multiple Scattering** The hit position in the third MSGC is $x'_3 = x_3 + d\theta_{ms}$, where θ_{ms} is the multiple-scattering angle due to material in the central detector. Again looking at the residual

$$\Delta x = \frac{1}{2} (x_1 + x'_3) - x_2 \quad (\text{B.4})$$

$$\sigma_{\Delta x}^2 = \frac{3}{2} \sigma_{\text{space}}^2 + \frac{1}{4} d^2 \sigma_{ms}^2 \quad (\text{B.5})$$

If the residual is determined at two different detector spacings, a and b , then the spatial resolution is

$$\sigma_{\text{space}} = \sqrt{\frac{2}{3} \frac{b^2 \sigma_{\Delta x a}^2 - a^2 \sigma_{\Delta x b}^2}{b^2 - a^2}} \quad (\text{B.6})$$

and the standard deviation of the multiple-scattering angle is

$$\sigma_{ms} = 2 \sqrt{\frac{\sigma_{\Delta x b}^2 - \sigma_{\Delta x a}^2}{b^2 - a^2}} \quad (\text{B.7})$$

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