Study of a GEM tracker of charged particles
for the Hall A high luminosity spectrometers
at Jefferson Lab

MASTER THESIS

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A buona volontà,
non manca facoltà.

*Italian proverb*

*Where there is a will there is way.*
Abstract

This thesis work has been dedicated to the development of a new Gas Electron Multiplier (GEM) tracker of high energy charged particles, for high luminosity spectrometers in Hall A at Jefferson Lab, where the 12 GeV upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) should be completed in 2014. Already five experiments involving this GEM tracker have been approved by the JLab Program Advisory Committee (PAC) and will investigate aspects that concern the fundamental structure of protons and neutrons. Three of them are related to nucleon form factors, respectively labelled as GEP5, GEN2 and GMN, and will require a new spectrometer named the Super Bigbite Spectrometer (SBS). Members of the Italian collaboration working at JLab are in charge for the development and construction of the Front Tracker of the SBS, as well as for the development of the electronics for all SBS trackers. The SBS Front Tracker will be composed of two 10 x 20 cm$^2$ silicon strip planes and six 40 x 150 cm$^2$ GEM chambers, identically made up of three adjacent 40 x 50 cm$^2$ triple-GEM modules.

In this thesis, the general physical principles of charged particle detection with gas detectors have been theoretically introduced, to provide a basis for the understanding of the functioning of GEM detectors. Hereafter, the structure and operating principles of single- and triple-GEM detectors have been described, as well as several particularities of their GEM foils and the typical composition of their fill-gases. The main characteristics of GEM trackers have also been outlined through a comparison with other types of trackers.

An overview has been given of the specifics of the SBS Front Tracker GEM chambers. Each 40 x 50 cm$^2$ module will be constituted of a cover frame, a mylar entrance foil, an entrance frame, a drift foil, a gridded drift frame, three GEM foils with their gridded GEM frames, and a read-out Printed Circuit Board (PCB) on a framed honeycomb structure. All frames, made of
insulating Permaglass TE630, will be 2 mm thick, except for respectively the cover (3 mm), the drift (3 mm) and the honeycomb frames (6 mm). GEM foils will consist of a 50 μm thick insulating Kapton layer cladded by two 3 μm thick copper electrodes, from which one will have twenty separated 20 x 5 cm² sectors. The read-out PCB will possess two layers of 0.5 μm thick copper strips (with a 400 μm pitch), at 90 degrees from each other and designed to get equal charge sharing between both read-out coordinates. Eighteen front-end electronic cards, each connected to 128 read-out strips and housing one APV25 chip, will be located on four backplanes around the borders of a module. One of the backplanes will be placed at 90 degrees with respect to the chamber, in the 2 cm gap between two adjacent modules. Multi-Purpose Digitizer (MPD) modules, compliant with the VME/VXS standard, will each be connected to two backplanes, in order to collect their analog outputs and to generate the digital signals for the data acquisition computer as well as the digital triggering signals for the front-end electronics. As for the high voltage system, the present plan is to generate independently seven floating voltages, the reference being provided to each read-out strip by the corresponding APV25 chip through an input protection circuit.

The first part of the original work reported in this thesis is the optimization of the design of the frame that separates two GEM foils of a 40 x 50 cm² triple-GEM module. The pursued goal has been to obtain a better spatial uniformity (over the active area of the module) of the continuous gas flow in the 2 mm gap between two GEM foils, since this gas flow should be spatially uniform in order to guarantee a homogeneous and stable detector response. A finite element study has been performed using a built-in model of the Computational Fluid Dynamics (CFD) add-on package of COMSOL Multiphysics, namely the Thin-Film Flow Model, which treats the laminar and isothermal flow of a thin fluid film between two large solid structures and solves the corresponding Reynolds equation. The choice of this model has also been determined by the fact that it uses a two-dimensional mesh, which limits the required computational capacity. For the simulated Ar-CO₂ (70/30) mixture, a typical total flow of about 3 chamber-volume renewals per hour (60 cm³/min) has been imposed at the frame inlets, wherefore the flow through the module has been assumed incompressible. The optimization of the frame design has been presented through mainly six simulations, showing progressive modifications of the simulated geometry. The first simulation corresponds to the initial prototype version of the
frame, possessing eighteen sectors, two inlets and two outlets. A second simulation has shown that adding a third inlet and a third outlet improves the overall flow uniformity, as the flows in the three six-sector rows become rather independent and similar. High velocity zones nearby inlets and outlets have also been reduced by replacing 90 degrees edges with 1.5 mm radius circular joints. In a third simulation, the number of stagnation zones has been decreased by reducing the number of short spacers from five to three, leading to a frame with twelve sectors which still meets the mechanical requirements related to the planarity of the GEM foils. The fourth simulation, in which openings in the spacers nearby the inlets and outlets have been enlarged from 15 mm to 20 mm, has not yielded a meaningful improvement of the gas flow uniformity. However, the fifth simulation has shown that introducing in the short spacers nine openings of 10 mm, instead of six openings of 15 mm, decreases the size of various stagnation zones. Finally, a sixth simulation has convinced us that doubling the number of 15 mm openings in the long spacers does not significantly improve the flow uniformity and thus the geometry of the fifth simulation has been selected as the basis for a new frame design. A confirming quantitative analysis of the flow uniformity in the aforementioned simulations has been made using the values of the velocity magnitude in 2000 points located on a rectangular grid. The extracted velocity distributions of the six simulations have been compared through their cumulative frequencies for several fractions of their mean velocity. Due to the linearity of the model, these cumulative frequencies do not depend on the total gas flow. It has been found that for the ultimately chosen frame design, about 9% of the points have a velocity lower than one half of the mean velocity (against 19 to 20% for the original frame design) and also about 9% of the points have a velocity greater than 1.5 times the mean velocity (against nearly 15% for the original frame).

In the simulation of the chosen frame design, a small value (0.1642 Pa for a total flow of 60 cm³/min) has been obtained for the total pressure loss across the module. This simulation has also indicated that the inlets and outlets are responsible of a very large fraction of the total pressure loss. In future work, it would be useful in our opinion to make a (more capacity consuming) three-dimensional model of the frame which accurately evaluates the pressure losses across a single module, in order to confirm for example whether it is advantageous to connect in series the gas systems of the three GEM modules of a chamber.
The second part of the reported original thesis activities concerns the development of a LabVIEW program for the remote control of the high voltage test of GEM foils, which belongs to the quality check procedures of the manufacturing process of a GEM module. An overview has been given of the module assembling method and the quality checks to be performed on GEM foils, i.e. the optical inspection and the high voltage test. Especially the latter, in which the leakage current through the Kapton layer of the foil is measured when a voltage is applied between the external copper layers, plays a crucial role in indicating the presence of problematic manufacturing defects in GEM foils. In Catania, an electrometer Keithley 6517B will be used to both apply the voltage and measure the leakage current. The LabVIEW program that has been developed for its remote control, has been given a large flexibility. It is able to generate increasing as well as decreasing voltage sequences, made up of “steps” that each consist of a voltage ramp followed by a landing. The program also periodically triggers and retrieves current measurements, during a sequence but also while the applied voltage remains constant in between sequences. A sequence can be launched or aborted at any time and, apart from the number of steps and the voltage to reach, the operator can also select the ramp slope, the landing time and the “delay time” (representative of the period in between two current measurements, at least if the chosen combination of the parameters does not lead to voltage increments that exceed the 0.01 V precision). Based on the inserted parameters, the program automatically maximizes the number of voltage increments which constitute a ramp. Additional fine-tuning of the high voltage test can be achieved through the adjustment of the integration time of the electrometer’s analog-to-digital converter (to 1 or 2 Power Line Cycles) and the selection of the lower and upper range limits for the auto-ranging search process. Moreover, the operator can choose whether to use the built-in 20 MΩ current limiting resistor of the Keithley 6517B, as a protection for the GEM foil. The evolution of the applied voltage and the measured current can be followed on displayed graphs and are also recorded in text files on request.
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# Contents

List of Figures ix  
List of Tables xiv  

1 Introduction 1  
1.1 A short story of gas detectors 1  
1.2 Jefferson Lab and the 12 GeV upgrade of the CEBAF 5  
1.3 Nucleon form factors measurements planned in Hall A 10  
1.4 The mission of the INFN JLab12 group 16  
1.5 Overview of the thesis activities 17  

2 From gas detectors to GEM 18  
2.1 Physics behind gas detectors 18  
2.1.1 Interactions of charged particles with matter 19  
2.1.2 Interactions of photons with matter 24  
2.1.3 Ionization in gas detectors 27  
2.1.4 Neutralization in gas detectors 29  
2.1.5 Diffusion of ions and free electrons without electric field 30  
2.1.6 Drift and diffusion of ions and free electrons in an electric field 31  
2.1.7 Gas multiplication 32  
2.1.8 Discharges in gas detectors 34  
2.1.9 Basic operating modes of gas detectors 36  
2.2 The single-GEM detector 38  
2.2.1 Operation of a single-GEM detector 38  
2.2.2 Effective gain of a single-GEM detector 41  
2.3 The triple-GEM detector 43  
2.3.1 Operation of a triple-GEM detector 43  
2.3.2 Effective gain of a triple-GEM detector 44
# GEM chambers for the SBS Front Tracker

## 3 GEM chambers for the SBS Front Tracker

### 3.1 Choice of the GEM technology

### 3.2 Structure of the GEM chambers

#### 3.2.1 Geometry of a single chamber

#### 3.2.2 Geometry of a 40 x 50 cm² triple-GEM module

#### 3.2.3 The GEM foils

#### 3.2.4 The mechanical frames

#### 3.2.5 The 2D read-out planes

### 3.3 Electronics

#### 3.3.1 The front-end electronics

#### 3.3.2 The Multi-Purpose Digitizer modules

### 3.4 High voltage system

### 3.5 Proportional mode

## 4 Development activities

### 4.1 Study and optimization of the gas system

#### 4.1.1 Overview and motivation

#### 4.1.2 The COMSOL Multiphysics package

#### 4.1.3 COMSOL’s Thin-Film Flow Model

#### 4.1.4 Adopted approach

#### 4.1.5 Analysis and results

### 4.2 Quality control: high voltage test of GEM foils

#### 4.2.1 Overview of the assembling procedures and needs

#### 4.2.2 Quality control procedures for GEM foils

#### 4.2.3 Program development in LabVIEW for the remote control of the high voltage test

## 5 Conclusion

## A Previous and latest GEM frame designs
CONTENTS

B  Reichenberg’s formula 126
C  Sub-VIs of the HV test LabVIEW program 130

Bibliography 132
## List of Figures

1.1 The parallel-plate chamber ........................................ 3  
1.2 The single-wire counter ............................................ 3  
1.3 The Multi-Wire Proportional Counter .............................. 4  
1.4 The Micro-Strip Gas Chamber ....................................... 4  
1.5 The Micro-Mesh Gas Chamber (MicroMeGas) ....................... 4  
1.6 Schematic view of the present CEBAF ............................. 6  
1.7 Schematic layout of the CEBAF modifications required for the 12 GeV upgrade .................................................. 7  
1.8 Single virtual photon exchange in the elastic scattering of an electron by a nucleon, according to the Born approximation . 11  
1.9 Comparison of $\mu_{p}G_{E}^{p}/G_{M}^{p}$ from the JLab polarization data and Rosenbluth separation results ................................. 12  
1.10 Schematic view of the general set-up of the future GEP5 experiment ............................................................... 14  
1.11 Schematic view of the general set-up of the future GEN2 and GMN experiments .................................................. 15  
2.1 Stopping power versus energy for charged particles in air .... 23  
2.2 Cross-sections of photon interactions in NaI, as a function of energy ................................................................. 25  
2.3 The relative importance of photoelectric absorption, Compton scattering and pair production ............................... 26  
2.4 The first Townsend coefficient divided by the gas pressure, as a function of the reduced electric field in several noble gases .. 33  
2.5 Principle of the avalanche formation in a parallel-plate chamber 34  
2.6 Principle of the avalanche formation in a single-wire proportional counter .......................................................... 34  
2.7 Photon-mediated backwards formation of a streamer ........... 35
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>Cloud chamber photographs of the streamer and spark formation</td>
<td>35</td>
</tr>
<tr>
<td>2.9</td>
<td>The collected charge as a function of the applied voltage in thin-wire gas counters and the corresponding operating modes of these detectors</td>
<td>37</td>
</tr>
<tr>
<td>2.10</td>
<td>Schematic cross-section view of a single-GEM detector</td>
<td>39</td>
</tr>
<tr>
<td>2.11</td>
<td>Typical geometry features of GEM foils with biconical holes</td>
<td>39</td>
</tr>
<tr>
<td>2.12</td>
<td>Electron microscope picture of a standard-design GEM foil</td>
<td>39</td>
</tr>
<tr>
<td>2.13</td>
<td>Three examples of read-out plane geometries for GEM detectors</td>
<td>40</td>
</tr>
<tr>
<td>2.14</td>
<td>Qualitative operation scheme of a single-GEM detector</td>
<td>42</td>
</tr>
<tr>
<td>2.15</td>
<td>Schematic cross-section view of a triple-GEM detector</td>
<td>43</td>
</tr>
<tr>
<td>2.16</td>
<td>Discharge probability as a function of the gas gain for single, double and triple GEM detectors with an Ar/CO$_2$ (70/30) gas mixture</td>
<td>46</td>
</tr>
<tr>
<td>2.17</td>
<td>Principle of the double-mask manufacturing method of GEM foils</td>
<td>47</td>
</tr>
<tr>
<td>2.18</td>
<td>Principle of the single mask manufacturing method of GEM foils</td>
<td>47</td>
</tr>
<tr>
<td>3.1</td>
<td>Geometry of the Front Tracker GEM chambers</td>
<td>53</td>
</tr>
<tr>
<td>3.2</td>
<td>Positions of the electronics backplanes in a chamber</td>
<td>54</td>
</tr>
<tr>
<td>3.3</td>
<td>Schematic assembly view of the COMPASS design from which the SBS triple-GEM modules are derived</td>
<td>55</td>
</tr>
<tr>
<td>3.4</td>
<td>Schematic cross-section of a GEM module</td>
<td>55</td>
</tr>
<tr>
<td>3.5</td>
<td>Composition of the CERN made honeycomb plane</td>
<td>55</td>
</tr>
<tr>
<td>3.6</td>
<td>Schematic view of the high-voltage terminals and the connections for the protective resistors of the GEM foil sectors</td>
<td>56</td>
</tr>
<tr>
<td>3.7</td>
<td>Geometry of the strips on the read-out plane</td>
<td>59</td>
</tr>
<tr>
<td>3.8</td>
<td>Drawing of a GEM foil superimposed to the read-out plane</td>
<td>59</td>
</tr>
<tr>
<td>3.9</td>
<td>Schematic view of the read-out electronics chain</td>
<td>61</td>
</tr>
<tr>
<td>3.10</td>
<td>A front-end card with its APV25 chip, connected to a Flexible Printed Circuit</td>
<td>61</td>
</tr>
<tr>
<td>3.11</td>
<td>The Multi-Purpose Digitizer module</td>
<td>63</td>
</tr>
<tr>
<td>3.12</td>
<td>Principle of the input protection circuit of the APV25 chip</td>
<td>63</td>
</tr>
<tr>
<td>4.1</td>
<td>Schematic diagram of the situation to which the Thin-Film Flow Model applies</td>
<td>68</td>
</tr>
<tr>
<td>4.2</td>
<td>Velocity field obtained in the case of a frame with 2 sectors</td>
<td>74</td>
</tr>
<tr>
<td>4.3</td>
<td>Velocity field obtained in the case of a frame with 6 sectors</td>
<td>75</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

4.4 Simulation 1 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for the full frame in its first prototype version ................................................................. 78
4.5 Simulation 1 – Contour plot with logarithmic scale of the velocity magnitude obtained for the full frame in its first prototype version ................................................................. 79
4.6 Simulation 1 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for one of the two inlets in the first prototype version ........................................... 80
4.7 Simulation 1 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for an opening in a spacer of the full frame in its first prototype version .................... 80
4.8 Simulation 2 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for an 18-sectors frame with 3 inlets and 3 outlets ......................................................... 82
4.9 Simulation 2 – Contour plot with logarithmic scale of the velocity magnitude obtained for an 18-sectors frame with 3 inlets and 3 outlets ......................................................... 83
4.10 Simulation 2 bis – Inlet without circular joints. ......................... 84
4.11 Simulation 2 – Inlet with 1.5 mm radius circular joints. ............. 84
4.12 Simulation 3 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for a 12-sectors frame with 3 inlets and 3 outlets ......................................................... 85
4.13 Simulation 3 – Contour plot with logarithmic scale of the velocity magnitude obtained for a 12-sectors frame with 3 inlets and 3 outlets ......................................................... 86
4.14 Simulation 4 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for a 12-sectors frame with 3 inlets and 3 outlets, having enlarged openings in the spacers nearby inlets and outlets ......................................................... 88
4.15 Simulation 4 – Contour plot with logarithmic scale of the velocity magnitude obtained for a 12-sectors frame with 3 inlets and 3 outlets, having enlarged openings in the spacers nearby inlets and outlets ......................................................... 89
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.16</td>
<td>Simulation 5 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for a 12-sectors frame with 3 inlets and 3 outlets, having nine 10 mm openings in the spacers along the short side of the module. 90</td>
</tr>
<tr>
<td>4.17</td>
<td>Simulation 5 – Contour plot with logarithmic scale of the velocity magnitude obtained for a 12-sectors frame with 3 inlets and 3 outlets, having nine 10 mm openings in the spacers along the short side of the module. 91</td>
</tr>
<tr>
<td>4.18</td>
<td>Simulation 6 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for a 12-sectors frame with 3 inlets and 3 outlets, having nine 10 mm openings in the short spacers and eight 15 mm openings in the long spacers. 92</td>
</tr>
<tr>
<td>4.19</td>
<td>Simulation 6 – Contour plot with logarithmic scale of the velocity magnitude obtained for a 12-sectors frame with 3 inlets and 3 outlets, having nine 10 mm openings in the short spacers and eight 15 mm openings in the long spacers. 93</td>
</tr>
<tr>
<td>4.20</td>
<td>Percentage of the points that have a velocity lower than a given fraction of the mean velocity, compared for the six simulations. 98</td>
</tr>
<tr>
<td>4.21</td>
<td>Velocity magnitude on a linear scale and streamlines of the velocity field obtained for Simulation 1 rerun for a 600 cm³/min flow. 99</td>
</tr>
<tr>
<td>4.22</td>
<td>Velocity magnitude on a linear scale and streamlines of the velocity field obtained for Simulation 5 rerun for a 600 cm³/min flow. 100</td>
</tr>
<tr>
<td>4.23</td>
<td>Simulation 5 – Contour plot of the film-pressure variation $p_f$. 102</td>
</tr>
<tr>
<td>4.24</td>
<td>Picture of a frame being glued to a stretched GEM foil. 105</td>
</tr>
<tr>
<td>4.25</td>
<td>Drawing of the GEM stretcher. 105</td>
</tr>
<tr>
<td>4.26</td>
<td>Schematic view of the connections between the Keithley 6517B and the GEM foil. 108</td>
</tr>
<tr>
<td>4.27</td>
<td>Summary of the procedure for the high voltage test of GEM foils. 109</td>
</tr>
<tr>
<td>4.28</td>
<td>Front panel of the main program for the remote control of the high voltage test. 111</td>
</tr>
<tr>
<td>4.29</td>
<td>Structure of a step inside a sequence. 112</td>
</tr>
<tr>
<td>A.1</td>
<td>Previous design – all frames of the module assembled. 119</td>
</tr>
<tr>
<td>A.2</td>
<td>Previous design – the GEM frame. 120</td>
</tr>
</tbody>
</table>
A.3 Previous design – the GEM frame (3D side view) . . . . . . . . . . . 121
A.4 Previous design – a gas inlet/outlet of the GEM frame . . . . . . . 122
A.5 Latest design – all frames of the module assembled . . . . . . . . . 123
A.6 Latest design – the GEM frame . . . . . . . . . . . . . . . . . . . . . . . . 124
A.7 Latest design – a gas inlet/outlet of the GEM frame . . . . . . . . . 125
A.8 Latest design – a gas inlet/outlet of the GEM frame (3D view) 125
List of Tables

1.1 Approved experiments for the CEBAF 12 GeV upgrade, which will use the GEM detector being developed and built by the INFN collaboration ........................................ 8

2.1 Trackers’ properties compared for several tracking technologies ........................................ 51

4.1 Values of the parameters used to compute the dynamic viscosity of the Ar-CO₂ (70/30) mixture ........................................ 73

4.2 Comparison of the total inlet and outlet fluxes obtained in the six simulations ........................................ 94

4.3 Mean, minimum and maximum velocities of the 2000-points distributions of the six simulations ........................................ 96

4.4 Percentage of the points that have a velocity lower than a given fraction of the mean velocity, compared for the six simulations ........................................ 97

4.5 Mean, minimum and maximum velocities and percentage of the points that have a velocity lower than a given fraction of the mean velocity, for Simulations 1 and 5 rerun with a 600 cm³/min flow ........................................ 97
Chapter 1

Introduction

1.1 A short story of gas detectors

The history of the development of detectors for ionizing radiation is closely related to the discovery of ionizing radiation itself. The first two major milestones in this field are undoubtedly the discoveries of X-rays, by William Conrad Röntgen in 1895, and of radioactivity, by Antoine Henri Becquerel in 1896 (for uranium) and the spouses Marie and Pierre Curie in 1898 (for polonium and radium). In particular, Röntgen observed during his experiments that, when a voltage is applied to a pair of electrodes, the air in between them can conduct electricity when traversed by X-rays, whereafter Marie Curie noticed the same behaviour for the radiation emitted by uranium [1]. This effect became the operating principle of the first gaseous detectors of ionizing radiation, a group of radiation detectors also simply called gas detectors and which are widely in use in nuclear physics.

The first gas detectors were early versions of parallel-plate ionization chambers (cf. Figure 1.1), whose operating characteristics became well understood in 1899 thanks to Joseph John Thomson [1]. At the beginning of the 20th century, also coaxial cylindrical gas detectors, having as anode a thin wire on the axis of a cylindrical cathode (cf. Figure 1.2), were studied by Ernest Rutherford and Johannes Wilhelm Geiger. In 1928, these studies lead J.W. Geiger, assisted by his student Walther Müller, to the invention of the well-known Geiger-Müller counter [2]. Twenty years later, the single-wire proportional counter was introduced by Samuel Crowe Curran [3].

Since the mid-20th century, researchers tried to develop large gaseous detectors with a real space localization capability. Indeed, stacking many sep-
arate counters was not an attractive solution from the mechanical point of view, while other existing detectors, like the cloud chamber, the bubble chamber and the streamer chamber, involved making photographs instead using of a fast electronic read-out which strongly limited their rate capability [4]. The first major achievement in this matter came in 1968, when Georges Charpak proposed the Multi-Wire Proportional Chamber (MWPC) [5], a gas detector consisting of a set of thin, parallel and equally spaced anode wires, symmetrically sandwiched between two cathode planes – each anode wire acting as an independent counter (cf. Figure 1.3). This design also lead to the invention of the drift chambers and, later on, the Time-Projection Chambers (TPC). In drift chambers [5], for which several different designs exist, the particle tracking is based on the measurement of the drift time of the liberated electrons towards the nearest anode wire. Drift chambers have a much better spatial resolution than MWPC. The Time-Projection Chambers [7] also measure drift times but use a multi-wire endplate (or more recent two-dimensional tracking detector) in order to allow three-dimensional track reconstruction. The main limitation of wire-based trackers is that, due to space-charge build-up around the anode wires, their maximum achievable gain (and therefore their detection efficiency) decreases for increasing hit rates. With MWPC, the maximum rate capability is generally below 1 MHz/cm$^2$ [5].

In 1988, Anton Oed introduced the Micro-Strip Gas Chamber (MSGC) [8], which was the first example of the micro-pattern gas detectors. Today, this family counts more than twenty gas detector designs [9], which have as common characteristic that the distance between the anodes and cathodes of amplification regions is smaller than 1 mm. Their manufacturing is based on lithographic techniques used in microelectronics for the production of multi-layer printed circuit boards. The rate capacity problem of the wire-based chambers are overcome because the space charge effects are reduced by the fact that positive ions do not have to travel a long distance towards the cathodes and are quickly neutralized. In Micro-Strip Gas Chambers, the anodes and cathodes are thin metallic strips which are placed at typically 100 $\mu$m from each other on an insulating (or slightly conducting) support in front of a drift electrode (cf. Figure 1.4). This design is compatible with hit rates as high as 100 MHz/cm$^2$ [10], but is quite susceptible to aging and, most of all, to destructive discharges. With the aim to overcome these drawbacks, several other micro-pattern gas detectors have been invented, with various
Figure 1.1: The basic components of a parallel-plate chamber, which can for example be operated in ionization or avalanche mode.

Figure 1.2: The basic components of a single-wire counter, which can be operated in ionization, proportional or Geiger-Müller mode, depending on the applied voltage (adapted from [2]).

types of geometry. To name a few [12]:
- Detectors with a Micro-Strip geometry: e.g. Micro-Gap Chambers (MGC) and Micro-Well detectors,
- Microdot and Micropin detectors,
- Micro-Groove detectors,
- Detectors with a parallel-plate geometry: e.g. Micro-Mesh Gas chambers (MicroMeGas)
- Detectors with a hole geometry: e.g. “Compteur à Trous” (CAT) detectors and Gas Electron Multiplier (GEM) detectors.

Gas Electron Multipliers (GEM), which are the subject of this thesis, were proposed in 1997 by Fabio Sauli [13]. Together with MicroMeGas [14], GEM detectors are the most used micro-pattern gas detectors at present. The MicroMeGas detector is based on the parallel-plate avalanche chamber design and possesses a thick conversion region separated by a metallic micromesh from a very thin charge amplification region which is ended by a striped anode read-out plane (cf. Figure 1.5).
CHAPTER 1. INTRODUCTION

Figure 1.3: The Multi-Wire Proportional Counter [6].

Figure 1.4: The Micro-Strip Gas Chamber [11].

Figure 1.5: The Micro-Mesh Gas Chamber (MicroMeGas) [6].
1.2 Jefferson Lab and the 12 GeV upgrade of the CEBAF

According to the Standard Model of Particle Physics [15], matter is made of elementary particles belonging to two families: the quarks and the leptons. Quarks, which come in 6 kinds called flavors (Up, Down, Top, Bottom, Charm and Strange), interact mainly through the strong force and are found in composites, which are called hadrons. Leptons, however, are not subjected to the strong force and can be observed as isolated (free) particles. As an example, the atom consists of electrons, which belong to the lepton family, and the atomic nucleus, made up of protons and neutrons, which are hadrons generically called nucleons. The Standard Model also includes force-carrying elementary particles, which mediate three of nature’s fundamental interactions: the gluons for the strong force, the photons for the electromagnetic force and the $W^+$, $W^-$ and $Z$ bosons for the weak force. However, the fourth known force, gravity, is not included in the Standard Model. The Higgs boson has been introduced as the cause of an interaction through which particles acquire mass, but until today this suggested elementary particle remains hypothetical. The observation of the Higgs boson is one of the main purposes of the Large Hadron Collider at CERN.

The Thomas Jefferson National Accelerator Facility, also called Jefferson Lab or JLab, is located in Newport News, Virginia, U.S.A., and has as a primary mission to conduct fundamental research on the atomic nucleus at the nucleon and quark level and on how the strong force binds hadrons [16]. As a secondary mission, along with education, applied research is carried out at JLab with industry and university partners, e.g. on radiation detectors, medical imaging devices and various topics involving JLabs free-electron laser [17]. The fundamental research at JLab includes experiments with highly focused longitudinally polarized, continuous electron beams accelerated in the CEBAF, the Continuous Electron Beam Accelerator Facility. Figure 1.6 shows a schematic view of this facility as it is today. The CEBAF consists of two superconducting radiofrequency 0.6 GeV linear accelerators (LINACs), which are parallel to each other and linked by recirculating arcs, so that the electrons follow a sort of racetrack-shaped trajectory. One lap is 0.875 mile long [17], which is approximately 1.4 km. The electrons can travel inside the CEBAF for a distance as long as 5 laps and reach a maximal energy of 6 GeV.
When the desired energy is reached, the beam is sent simultaneously (on request) to the CEBAF’s experimental halls: Hall A, Hall B and Hall C. The summed beam current ranges from a few pA to 200 µA [19]. Today, thanks to an improved electron gun, the longitudinal polarization of the beam reaches up to 85% [20], meaning that it is possible to make approximately 85% of the electrons to have their spin axis aligned (or antialigned) with the direction of motion.

At the end of 2008, the construction was started at CEBAF for the so-called 12 GeV upgrade. The commissioning for this project is expected in 2013 and its completion in 2014 [21]. The present LINACs will be upgraded from 0.6 GeV to 1.1 GeV [22], which requires also to approximately double the refrigeration capacity and to adapt the existing 5-pass beam transport system [23]. With this upgrade, it will be possible to deliver energies up to 10.9 GeV to Halls A, B and C [24]. Apart from this, an extra 180° arc will be added, in order to deliver a 12.0 GeV beam to Hall D [24], which is to be built at the opposite end of the accelerator with respect to the three existing experimental halls. It was decided to retain the present total beam power limit of 1 MW [22], with a maximum beam current of 85 µA summed for Halls A, B and C, and of 5 µA for Hall D [24]. A schematic layout of the required modifications for the CEBAF 12 GeV upgrade is shown in Figure 1.7.

The CEBAF 12 GeV upgrade should allow the researchers to better investigate whether the quantum chromodynamics (QCD) theory for strong
interactions gives a full and complete description of hadronic systems. The research program will focus on 4 main areas [24]:

- Exotic hybrid mesons\(^1\) will be searched for in the GlueX experiment in Hall D, with the aim to understand the confinement of quarks.
- Various experiments will be dedicated to the study of the fundamental structure of protons and neutrons.
- Other experiments will focus rather on the physics of the nucleus, i.e. on how the nucleon-based models of nuclear physics arise as an approximation of the underlying quark-gluon structure described in QCD.
- Physics beyond the Standard Model will also be investigated. This program includes high precision studies of parity violation and tests of chiral symmetry and chiral anomalies [24].

The GEM detector to which this thesis is dedicated will be used as a charged particle tracker in several experiments of the upgraded Hall A, for example in the future Super Bigbite Spectrometer (SBS) or in the existing Bigbite Spectrometer (BB) [24]. Until now, five experiment proposals involv-

\(^1\)Ordinary mesons are hadrons made of one valence quark-antiquark pair. The Standard Model also predicts the existence of exotic mesons, among which exotic hybrid mesons, which differ from ordinary mesons by the presence of a valence gluon [25].
<table>
<thead>
<tr>
<th>Reference</th>
<th>Label</th>
<th>Full title</th>
<th>Apparatus</th>
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<tbody>
<tr>
<td>E12-07-109</td>
<td>GEP/GMN</td>
<td>Large acceptance proton form factor ratio measurements at 13 and 15(GeV/c)^2 using recoil polarization method</td>
<td>SBS (*) &amp; BB</td>
</tr>
<tr>
<td>E09-016</td>
<td>GEN2</td>
<td>Measurement of the neutron electromagnetic form factor ratio at high Q^2</td>
<td>SBS &amp; BB (*)</td>
</tr>
<tr>
<td>E09-019</td>
<td>GMN</td>
<td>Precision measurement of the neutron magnetic form factor up to Q^2 = 18.0(GeV/c)^2 by the ratio method</td>
<td>SBS &amp; BB (*)</td>
</tr>
<tr>
<td>E12-06-122</td>
<td>A1n</td>
<td>Measurement of neutron spin asymmetry A^n in the valence quark region using 8.8 GeV and 6.6 GeV beam energies and BigBite spectrometer in Hall A</td>
<td>HRS &amp; BB (*)</td>
</tr>
<tr>
<td>E12-09-018</td>
<td>SIDIS</td>
<td>Measurement of the semi-inclusive pion and kaon electroproduction in DIS regime from transversely polarized ³He target using the Super Bigbite and BigBite Spectrometers in Hall A</td>
<td>SBS &amp; BB (*)</td>
</tr>
</tbody>
</table>

Table 1.1: Approved experiments for the CEBAF 12 GeV upgrade, which will use the GEM detector being developed and built by the INFN collaboration [26][27][28]. (*) indicates in which spectrometer this GEM detector will be included. SBS stands for Super Bigbite Spectrometer, BB for BigBite spectrometer and HRS for High Resolution Spectrometer.
ing this GEM detector have been approved by the JLab Program Advisory Committee (PAC) \cite{26}\cite{27}\cite{28}. Table 1.1 gives an overview of these experiments, all of which explore aspects related to the fundamental structure of protons and neutrons.

The GEP5, GEN2 and GMN experiments are dedicated to the investigation of the nucleon form factors at high quadri-momentum transfer and are discussed in section 1.3.

In the A1n experiment, inclusive Deep-Inelastic Scattering\footnote{In Deep-Inelastic Scattering, the energy and momentum transferred by the lepton (e.g. the electron) to the target nucleon is high enough to reveal the internal structure of this nucleon. In fact, according to Heisenberg’s uncertainty principle, scattering with high momentum and energy transfers corresponds to the involvement of very small spatial and temporal structures, i.e. the components of the nucleon (quarks and gluons). When only the scattered lepton is detected, the experiment is called inclusive, while it is called semi-inclusive when at least one additional particle in the final state (generally a hadron) is detected in coincidence with the scattered electron \cite{29}.} of polarized electrons on the neutrons of a polarized $^3$He target will be measured. The neutron spin asymmetry $A_1^n$ (cf. \cite{30}) will be determined for values of the Bjorken scaling variable\footnote{The definition of the Bjorken scaling variable is $x_{Bj} = \frac{Q^2}{2M\nu}$, where $Q^2$ is the negative of the squared quadrirmomentum of the exchanged virtual photon, $M$ is the target nucleon mass and $\nu$ is the energy loss of the electron due to the scattering \cite{29}.} $x_{Bj}$ higher than 0.6, which has never been done before. The predictions of various theoretical models will be checked, including those of the perturbative quantum chromodynamics (pQCD) model, for which a disagreement was found with previous measurements at $x_{Bj}=0.6$. By confronting especially the pQCD calculations of $A_1^n$ with the results of this upcoming experiment, considerable insight should be gained into the role of the orbital angular momentum of the quarks in the nucleon wave function. For a complete overview of the aims and specifics of this experiment, we refer the reader to reference \cite{30}.

The SIDIS experiment mentioned in Table 1.1 will study a Semi-Inclusive Deep-Inelastic Scattering process of polarized electrons on the neutrons of a polarized $^3$He target, for which in the final state a $\pi^+$, a $\pi^-$, a $K^+$ or a $K^-$ will be observed in addition to the scattered electron. We refer the reader to reference \cite{31} for more information on this approved experiment that “has significant potential for the discovery of new effects in hadron physics” \cite{31}.
1.3 Nucleon form factors measurements planned in Hall A

From the Sachs nucleon form factors, respectively the electric form factor $G_E(Q^2)$ and the magnetic form factor $G_M(Q^2)$, we can obtain a nucleon’s radial charge distribution and magnetic moment. In a non-relativistic system, $G_E(Q^2)$ could be interpreted as the Fourier transform of the nucleon’s charge distribution and $G_M(Q^2)$ as the Fourier transform of its magnetization distribution, but in reality the nucleon form factors are determined in conditions such that relativistic effects should be taken into account, which complicates the expression that links them to the nucleon’s charge and magnetization distributions, as well as our interpretation (see [32]).

Traditionally, the Sachs nucleon form factors have been experimentally determined through the differential cross-section of the elastic scattering of electrons on nucleons, using the Rosenbluth separation method. In the Born approximation, the electromagnetic interaction between the electron being elastically scattered by a target nucleon is carried by a single virtual photon, as represented in Figure 1.8, and the dependence of the elastic scattering differential cross-section on $G_E(Q^2)$ and $G_M(Q^2)$ is given by the Rosenbluth formula [29]:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{G^2_E(Q^2) + \frac{Q^2}{4M^2}G^2_M(Q^2)}{1 + \frac{Q^2}{4M^2}} + \frac{Q^2}{4M^2}2G^2_M(Q^2)\tan^2 \frac{\theta_e}{2}, \quad (1.1)$$

where $Q^2$ is the negative of the squared quadriradial momentum $q^2$ of the exchanged virtual photon, $M$ is the mass of the target nucleon, $\theta_e$ is the electron scattering angle and the Mott differential cross-section is given by:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{Z^2 (\frac{e^2}{4M})^2 \cos^2 \frac{\theta_e}{2}}{4p_0^2 \sin^4 \frac{\theta_e}{2} \left(1 + \frac{2p_0}{M} \sin^2 \frac{\theta_e}{2}\right)}, \quad (1.2)$$

where $p_0$ is the momentum of the incident electron and $e$ the electron’s charge. Note that the limiting values of the nucleon form factors at $Q^2 = 0$ are $G_E^p(0) = 1$, $G_M^p(0) = 2.79$, $G_E^n(0) = 0$ and $G_M^n(0) = -1.91$.

In the Rosenbluth separation method, the scattering differential cross-section is measured at fixed values of $Q^2$ for various scattering angles $\theta_e$. The obtained differential cross-sections are divided by the Mott differential cross-section and plotted as a function of $\tan^2(\theta_e/2)$, so that $G_M(Q^2)$ is determined.
CHAPTER 1. INTRODUCTION

Figure 1.8: Single virtual photon exchange in the elastic scattering of an electron by a nucleon, according to the Born approximation.

from the slope of the obtained straight line and then $G_E(Q^2)$ is deduced from the intercept at $\tan^2(\theta_e/2) = 0$ using the value of $G_M(Q^2)$ [29].

With the determination method based on the Rosenbluth separation, it has been long believed that the ratios $G^p_E(Q^2)/G^p_M(Q^2)$ and $G^n_E(Q^2)/G^n_M(Q^2)$ are constant, the former being equal to 1/2.79 and the latter to 1/(-1.91) [29]. However, in 1968, it was shown by Akhiezer and Rekalo [33] that their recoil polarization method (or double polarization method), already proposed in 1957, was a more sensitive technique to determine $G^p_E/G^p_M$ and, when this method was applied at Jefferson Lab at the beginning of the 21st century, the $G^p_E/G^p_M$ ratio was found to decrease linearly with $Q^2$, from 1 (GeV/c)$^2$ to 8.5 (GeV/c)$^2$ (cf. Figure 1.9).

The recoil polarization method is based on the measurement of the polarization of recoil nucleons on which longitudinally polarized electrons were elastically scattered. If the target nucleons are not polarized, the method consists in measuring the two non-zero components of the polarization of the recoil nucleon, the transverse polarization $P_t$ and the longitudinal polarization $P_l$. In the Born approximation, the ratio of the electric and magnetic form factors is then obtained by [40]:

$$\frac{G_E(Q^2)}{G_M(Q^2)} = \frac{-P_t E_{\text{beam}} + E_e}{P_l 2M} \tan \frac{\theta_e}{2},$$

where $E_{\text{beam}}$ and $E_e$ are the energy of the incident and the scattered electron respectively, $M$ is the mass of the target nucleon and $\theta_e$ is the electron scattering angle.
Figure 1.9: Comparison of $\mu_p G_E^p/G_M^p$ from the JLab polarization data [34][35][36] and Rosenbluth separation results [37][38]. $\mu_p = 2.79$ and units are such that $c = 1$. JLab Rosenbluth results from are shown as open and filled triangles. The dashed curve is a fit of Rosenbluth data [39]; the solid curve is a linear fit valid above $Q^2 \sim 0.4 \text{(GeV/c)}^2$, given by $\mu_p G_E^p/G_M^p = 1.0587 - 0.14265 Q^2$. 

A third method is a double polarization technique successfully adopted for neutron form factor measurements, which uses the elastic scattering of a longitudinally polarized electron on a polarized nucleon, at constant detection angles for the scattered electron and the recoiling nucleon. The form factor ratio is obtained from the determined beam helicity asymmetry $A = \Delta/\Sigma$, given that the differential cross-section of the elastic scattering of longitudinally polarized electrons on polarized nucleons is $\frac{d\sigma}{d\Omega} = \Sigma + h\Delta$, where $\Sigma$ is the unpolarized elastic differential cross-section, $\Delta$ is the “polarized part” and the helicity $h = \pm 1$ [41].

The GEP5 experiment, to be performed in Hall A at JLab using the future 11 GeV electron beam, will apply the recoil polarization method (with equation (1.3)) to measure the proton form factor ratio in the semi-inclusive elastic scattering of longitudinally polarized electrons on an unpolarized liquid hydrogen target, for $Q^2$ up to 15 GeV [40]. The planned experimental set-up is schematized in Figure 1.10. The scattered electrons will be detected in a GEM tracker and in the existing lead-glass BigCal calorimeter, while the recoil protons will be analyzed in the future Super Bigbite Spectrometer (SBS).

The Super Bigbite Spectrometer is a set of components that will be used in different configurations in several experiments. In its GEP5 configuration, it will be composed of [24]:

- two 10 x 20 cm$^2$ silicon strip planes, belonging to the Front Tracker (not shown in Figure 1.10);
- a 48D48 dipole, which bends the track of the recoil proton so that its momentum can be determined (and which provides a rotation of the recoil proton spin around the direction of the magnetic field so that, in the optimal case, the proton polarization becomes normal to the proton momentum);
- six consecutive 40 x 150 cm$^2$ GEM chambers, part of the Front Tracker, whose role is to define “initial” track of the recoil proton needed both for the determination of the proton momentum (with the help of the dipole) and for polarimetry;
- a CH$_2$ polarimeter in which the recoil proton is scattered (in yellow on Figure 1.10);
- a Second Tracker consisting of four consecutive 50 x 200 cm$^2$ GEM chambers, needed to provide the recoil proton’s secondary trajectory,
Figure 1.10: Schematic view of the general set-up of the future GEP5 experiment [24].

whose azimuthal asymmetry with respect to the “initial” track allows to determine the proton’s transverse and longitudinal polarization components:

- a second CH₂ polarimeter (in yellow on Figure 1.10);
- a Third Tracker consisting of four consecutive 50 x 200 cm² GEM chambers, which is associated to the second CH₂ polarimeter in order to either analyze the polarization of protons that have not been scattered in the first polarimeter or measure the proton polarization for a second time;
- a segmented hadron calorimeter, to provide a trigger with a high energy threshold.

The important features of the SBS are its ability to support high luminosities (up to ≈ 8 · 10³⁸ electrons/(nucleon·cm²·s) in the GEP5 experiment) and very forward scattering angles (down to 3.5°), its large solid angle and large momentum acceptance (compared to the acceptance of the existing Hall A spectrometer) [24]. Note that the high achievable luminosity is essential to access the processes with small cross-sections that will be investigated.

The GEN2 and the GMN semi-inclusive experiments will both investigate neutron form factors. They will have essentially the same set-up, shown in Figure 1.11, except for a main difference concerning the targets: a polarized ³He gas target is foreseen for GEN2 [41] and an unpolarized liquid deuterium...
target for GMN [42]. In the electron arm in Figure 1.11, the first GEM tracker, following the BigBite magnet, will consist of three chambers of the GEP5 Front Tracker, whereas two chambers of the GEP5 Second Tracker will constitute the second GEM tracker [24]. In the hadron arm, the GEP5 hadron calorimeter will be used, since it can also function as an efficient neutron detector with very good position resolution [24].

In the GEN2 experiment, the electromagnetic form factor ratio of the neutron $G_E^n/G_M^n$ will be measured at $Q^2 = 5.0, 6.8$ and $10.2 \text{ (GeV/c)}^2$ in double polarized semi-exclusive $^3\text{He}(e,e'\text{n})pp$ scattering, in quasi-elastic kinematics, through the measurement of the transverse asymmetry $A_\perp$ of the cross-section [41].

The neutron magnetic form factor $G_M^n(Q^2)$ will be measured in the GMN experiment for $Q^2 = 3.5, 4.5, 6.5, 8.5, 10, 12, 13.5, 16$ and $18 \text{ (GeV/c)}^2$, using the “ratio method”, in which $G_M^n(Q^2)$ is extracted from the ratio [42]:

$$R = \frac{\frac{d\sigma}{d\Omega}}{\frac{d\sigma}{d\Omega}}\bigg|_{d(e,e'\text{n})}.$$  \hspace{1cm} (1.4)

This method thus requires the measurements of both the differential cross-sections of the neutron-tagged and the proton-tagged quasi-elastic scattering by deuteron.
1.4 The mission of the INFN JLab12 group

The development and set-up of the Super Bigbite Spectrometer is carried out by a collaboration that involves, apart from JLab’s Hall A, seven universities in the USA, the University of Glasgow (Scotland) and our Italian group belonging to the *Istituto Nazionale di Fisica Nucleare* (INFN).

In this scope, the INFN group has the responsibility for the development and the construction of the SBS Front Tracker, as well as for the development of the electronics for all the SBS trackers.

The main requirements for the SBS tracking system are derived from the needs of the upcoming nucleon form factor experiments and more generally from the optimal exploitation of the future Hall A high luminosity and high energy beam (energy up to 11 GeV) [24]. They are [24][43]:

- The ability to sustain a high hit rate up to 1 MHz/cm$^2$ (a high background rate of $\approx$500 kHz/cm$^2$ will be mainly due to soft photons).
- A moderately high acceptance (from 40 x 150 cm$^2$ to 80 x 300 cm$^2$).
- A 0.5% momentum resolution and 0.5 mrad angular resolution at 8 GeV.
- The ability to tolerate the residual magnetic field of the dipole at about 110 cm from the dipole center (up to $\approx$1 kGauss).
- To be contained within $\approx$110 cm and $\approx$180 cm after the dipole magnet.

In addition, the following qualitative functionalities are also considered during the development of the tracking system [24]:

- The ability to be relocated and reconfigured in different positions in the same spectrometer and in the BigBite spectrometer.
- The ability to provide performances optimized to the different experiments, with minimum modification (e.g. change in spatial resolution).

Since 2009, the INFN group has built a prototype GEM tracker consisting of three 10 x 10 cm$^2$ modules. Also a first 40 x 50 cm$^2$ prototype module has been constructed and tested at the INFN, at DESY (in November/December 2009) and at CERN (in June/July 2011). As the project should soon enter its pre-production phase, more 40 x 50 cm$^2$ modules will be built in the coming months.
1.5 Overview of the thesis activities

As we already mentioned in this first chapter, the development of a GEM tracker has been the object of the thesis work. In our second chapter, we give a theoretical overview of the general physical principles involved in charged particle detection with gas detectors, whereafter the working principles and important features of Gas Electron Multiplier (GEM) detectors are introduced.

The third chapter describes the global structure and the specifics of the GEM tracker under development for the Super Bigbite Spectrometer in particular. Finally, the original activities carried out on two principal topics are reported in the fourth chapter.

Firstly, a finite element study of the gas flow in a 40 x 50 cm$^2$ module of the GEM tracker has been performed using the COMSOL Multiphysics software. The design of the frame that separates two GEM foils in such a module has been optimized from the point of view of the spatial uniformity of the gas flow, taking also mechanical requirements into account. The results of essentially six simulations, presenting gradual modifications of the frame geometry, are qualitatively and quantitatively discussed. For the ultimately chosen frame design, also a brief (mostly qualitative) analysis of the pressure losses throughout the module is given.

Secondly, a LabVIEW program has been developed for the remote control of the high voltage test belonging to the quality control procedures of the manufacturing process of a GEM module. An overview is given of the module assembling method and the associated quality checks on GEM foils, especially the high voltage test. At the University of Catania, this high voltage test will be performed with the Keithley 6517B electrometer. We describe the set-up of this instrument and its remote control, whereupon the philosophy of the developed program is detailed, as well as its main parameters and operating options.
Chapter 2

From gas detectors in general to Gas Electron Multipliers (GEM) in particular

2.1 Physics behind gas detectors

As GEM detectors belong to the large family of gaseous ionization detectors, we will first outline important physical aspects which are common to all of these detectors. Our discussion will be focused essentially on the detection of charged particles, since this thesis is dedicated to a GEM tracker of charged particles (in the first place, protons or electrons, depending on the experiment). This detection process relies on the specific interactions of the charged particle with the gas inside the detector that lead to the ionization of gas molecules. The electronic signal indicating the detection of the particle is induced by the drift towards the detector’s anode and cathode of respectively the free electrons and ions created in the gas. Depending on the operating mode of the detector, all or only a part of these drifting electron-ion pairs are directly created by the detected particle.

This chapter starts with the study of the most probable interactions with matter of charged particles, but also of photons because, as we will explain further, those are closely associated to the detection of charged particles. Moreover, we know that the GEM detectors of the SBS Front Tracker will be exposed to a significant background flux of (soft) photons (cf. section 1.4). Photons of sufficiently high energy, such as X- and γ-rays, can be ionizing particles, but they first need to be converted into a charged particle which
hereafter produces most or all of the ionization commonly attributed to the initial photon. For this reason, the photon is called an “indirectly ionizing” particle. Hereafter, we will continue our chapter with a discussion of ionization processes in general, as well as of the recombination of charges that can occur in gas detectors. The movement of the free electrons and ions, due to diffusion and drift, will also be discussed. Then, we will introduce a key aspect of many gas detectors (GEM detectors included): the gas multiplication, which is how electron-ion pairs can be multiplied in a so-called avalanche process. Finally, we will close this section with an overview of the main operating modes of gas detectors.

2.1.1 Interactions of charged particles with matter

When a fast charged particle is crossing a gaseous or condensed medium, it will interact with it most often through electromagnetic interactions, whose probability is many orders of magnitude greater than for strong or weak interactions [5]. Inelastic Coulomb collisions with atomic electrons and elastic Coulomb collisions with nuclei are the two most probable electromagnetic processes [4]. We will focus here on the first ones because they allow particle detection thanks to the energy transfer that leads to ionization and excitation of the medium’s atoms. These inelastic collisions can indeed be either close collisions, in which the transferred energy is more than large enough to remove an electron from an atom and thus ionization occurs, or distant collisions, involving a smaller energy transfer which leads to ionization only if the transferred energy is larger than the ionization potential of the atom. If this is not the case, the transferred energy will be such as to allow an atomic electron to be raised to a higher energy level within the atom, which is called excitation. Excited atom will have the tendency to return to their ground state through the emission of deexcitation photons (typically in the UV region).

Brehmsstrahlung, Cherenkov and transition radiation are other possible electromagnetic interactions of charged particles with matter, but at the energy of interest they are negligible compared to the two previously mentioned processes, at least for heavy charged particles. In fact, a distinction should be made here between so-called heavy and light charged particles. The latter ones are electrons and positrons, while the former ones are simply charged particles heavier than electrons, like for example muons, pions, protons and
α-particles [4]. An important difference between these two particle categories is that, for light charged particles, the three aforementioned radiation emission processes can contribute significantly to the energy loss of the particle in certain conditions (at high energies and in materials of high atomic number [2]), whereas for heavy charged particles, the inelastic Coulomb scattering is nearly solely responsible for the particle energy loss, except for additional effects that arise in the case of heavy nuclei and that are not discussed here (cf. [2]). Note that, due to their small mass, light charged particles will also suffer large deviations in collisions with orbital electrons and, therefore, follow a much more tortuous path through matter than heavy charged particles.

The energy loss of particles happens in discrete steps and is a statistical process. For example, two identical heavy charged particles will not in general suffer the same number of inelastic collisions, and thus the same energy loss, in strictly identical conditions. However, the mean differential energy variation $\left(\frac{dE}{dx}\right)_{\text{coll}}$ (variation per unit length) of a heavy charged particle due to inelastic Coulomb collisions with atoms of a pure element can be computed in a fairly accurate way in the relativistic quantum mechanics framework using the Bethe and Bloch formula [5]:

$$
\left(\frac{dE}{dx}\right)_{\text{coll}} = -\frac{2\pi N_A z^2 e^4 Z \rho}{m_e c^2 A \beta^2} \left\{ \ln \left( \frac{2 m_e c^2 \beta^2 E_{\text{max}}}{I(1 - \beta^2)} \right) - 2 \beta^2 \right\}
$$

(2.1)

where $N_A$ is the Avogadro number, $z$ is the charge of the projectile, $e$ and $m_e$ are the electron charge and mass, $c$ is the speed of light in vacuum, $Z$, $A$ and $\rho$ are respectively the atomic number, the atomic mass and the density of the medium, $\beta = \frac{v}{c}$ is the velocity $v$ of the projectile expressed in units of the speed of light $c$, $E_{\text{max}}$ is the maximum allowed energy transfer in a single collision and $I$ is the effective ionization potential.

Generally, an experimentally determined value is used for $I$, although the formula $I = 12eV \cdot Z$ gives rather a good approximation [5]. As for the maximum allowed energy transfer in each collision $E_{\text{max}}$, two-body relativistic kinematics [4] gives

$$
E_{\text{max}} = \frac{2 m_e c^2 \beta^2}{1 - \beta^2} \left( \frac{1 + \beta^2}{1 - \beta^2} + \left( \frac{m_e}{m_p} \right)^2 \right)
$$

(2.2)

in which appears $m_p$, the mass of the projectile. The dependence of the Bethe and Bloch formula on the mass of the projectile is however quite weak
when heavy charged particles are considered. Indeed, since $m_p >> m_e$, the expression (2.2) can be simplified as follows [4]:

$$E_{\text{max}} = \frac{2m_ec^2\beta^2}{1-\beta^2},$$  \hspace{1cm} (2.3)

and thus, in this approximation, the differential energy variation of the particle does no longer depend on its mass.

Since the logarithmic term in (2.1) varies slowly with the projectile velocity, at non-relativistic energies, the stopping power $S = -(\frac{dE}{dx})_{\text{coll}}$ is dominated by the overall $1/\beta^2$ factor. It decreases with increasing velocity until $v \approx 0.96c$, where it reaches a minimum at which the particles are called “minimum ionizing particles” [4]. The value of the mass stopping power, defined as $s = -\frac{1}{\rho} \frac{dE}{dx}$, is more or less the same for all types of minimum ionizing particles (even light charged particles) and corresponds typically to about $2\text{ MeV} \cdot g^{-1} \text{cm}^2$ in light matter [2]. When the velocity increases above $v \approx 0.96c$, the $1/\beta^2$ factor in (2.1) becomes nearly constant and so, according to Bethe and Bloch, the stopping power of a heavy charged particle should increase again because of the logarithmic term in their formula.

At high energies, however, the Bethe and Bloch formula breaks down. A saturation is indeed observed for the stopping power instead of a logarithmic increase with increasing velocity. This saturation is caused by the so-called density effect [4] that arises from the fact that the electric field of the charged particle tends to polarise the atoms along its path and this polarization shields electrons far from this path from the full electric field intensity of the charged particle. Therefore, collisions with these outer lying electrons contribute less to $\left(\frac{dE}{dx}\right)_{\text{coll}}$ than according to the Bethe-Bloch formula and this effect is more important in materials with higher densities because the induced polarization is greater.

Also at very low energies, the Bethe and Bloch formula, that is based on the assumption that the atomic orbital electron is stationary with respect to the incident particle, is no longer valid. In fact, the incident particle has a velocity comparable to or smaller than that of the electron, which induces several complicated effects that make the stopping power reach a maximum before dropping sharply with decreasing velocity. The most important of these effects for a positively charged particle is the tendency to pick up electrons from the medium and progressively reduce its effective charge. To correct the Bethe and Bloch formula for respectively the density effect (at
CHAPTER 2. FROM GAS DETECTORS TO GEM

high energies) and the several effects at very low energies, a density correction \( \delta \) (see [4]) and a shell correction \( C \) (see [4]) can be inserted in the following way:

\[
\left( \frac{dE}{dx} \right)_{\text{coll}} = -\frac{2\pi N_{A} z^{2} e^{4}}{m_{e}c^{2}} \frac{Z \rho}{A \beta^{2}} \left\{ \ln \frac{2m_{e}c^{2} \beta^{2} E_{\text{max}}}{I^{2}(1 - \beta^{2})} - 2\beta^{2} - \delta - 2 \frac{C}{Z} \right\}. \tag{2.4}
\]

As far as electrons are concerned, the basic mechanism of inelastic collisions with atomic electrons are the same as for heavy charged particles but nevertheless the formula (2.4) is not valid as such. Corrections have to be applied for two reasons [4]:

- the Bethe and Bloch formula is based on the assumption that the incident particle remains undeflected during the collision process, which is completely invalid for electrons because the particles involved in the collision share the same mass. The energy transfer can go up to half of the kinetic energy of the incident particle.
- in the case of electrons, the calculation should be based on the indistinguishability of the two particles involved in the collision.

The following formula [4] can be used to compute the differential energy variation of electrons due to inelastic Coulomb collisions:

\[
\left( \frac{dE}{dx} \right)_{\text{coll}} = -\frac{2\pi N_{A} z^{2} e^{4}}{m_{e}c^{2}} \frac{Z \rho}{A \beta^{2}} \left\{ \ln \frac{\tau^{2}(\tau + 2)}{2(I/m_{e}c^{2})^{2}} + F(\tau) - \delta - 2 \frac{C}{Z} \right\}, \tag{2.5}
\]

where \( \tau \) is the kinetic energy of the electron in units of \( m_{e}c^{2} \) and

\[
F(\tau) = 1 - \frac{\beta^{2} \frac{\tau^{2}}{\tau} - (2\tau + 1) \ln 2}{(\tau + 1)^{2}}. \tag{2.6}
\]

Figure 2.1 shows the energy dependence of the stopping power, measured for several types of charged particles moving through air. Observe the logarithmic scale for the particle energy and the different relative positions of the curves depending on the particle mass. From this figure, we can also see that, since the stopping power of is proportional to \( z^{2} \), \( \alpha \)-particles, for example, lose energy at a higher rate than protons of the same velocity.

Note that in the case of compounds and mixtures, direct measurements are required in order to get accurate values for the stopping power of charged
Figure 2.1: The stopping power as a function of the projectile energy, for respectively electrons, pions, muons, protons, deuterons and $\alpha$-particles in air [2].

particles. However, a good approximation can be obtained for compounds using the same formulas as for pure elements but with the following effective values of $Z$, $A$, $I$, $\delta$ and $C$ [4]:

\[
Z_{\text{eff}} = \sum_i a_i Z_i \quad A_{\text{eff}} = \sum_i a_i A_i \\
I_{\text{eff}} = \sum_i a_i Z_i \ln I_i \frac{1}{Z_{\text{eff}}} \\
\delta_{\text{eff}} = \sum_i a_i Z_i \delta_i \frac{1}{Z_{\text{eff}}} \quad C_{\text{eff}} = \sum_i a_i C_i
\]

(2.7)

where $i$ refers to an element and $a_i$ is the number of atoms of element $i$ in a molecule of the compound.
2.1.2 Interactions of photons with matter

Photons are neutral particles without a rest mass. The behaviour of X-rays and γ-rays in matter is therefore very different from that of charged particles. The main electromagnetic interactions of the photons are basically of three types:

1. Photoelectric absorptions,
2. Rayleigh and Compton scattering,
3. Absorption because of electron-positron pair production.

Also nuclear dissociation reactions are possible, but they are much less common [4] and will not be discussed here. At low energies, the photoelectric absorption is the dominant process; at intermediate energies, the Compton scattering becomes more probable; and finally, at high energies, the pair production takes the lead, as can be seen from the cross-sections on Figure 2.2. Figure 2.3 shows the transitions from one dominant process to another, depending on the atomic number of the absorber.

An important point is that, while charged particles slow down progressively through many interactions with atoms, photons often interact with the sensitive medium of a gas detector in only one single localized event [5], in which they are either absorbed or scattered with a significant angle (such that, for example, they completely leave the beam to which they initially belonged). A beam of photons is therefore not degraded in energy after passing through a thickness of matter [4], but it is only attenuated in intensity. The attenuation is known to be exponential with respect to the thickness of the absorber, as expressed in the following formula:

$$I(x) = I_0 e^{-\mu x},$$  \hspace{1cm} (2.8)

where \(x\) is the thickness of the absorber, \(I_0\) is the initial beam intensity, \(I\) is the attenuated intensity and \(\mu\) is the mass attenuation coefficient, which is equal to the total absorption cross-section multiplied by the number of molecules per unit volume [5]. This cross-section is much smaller than the inelastic scattering cross-section of charged particles with atomic electrons and X-rays and γ-rays are therefore much more penetrating in matter [4].

In photoelectric absorption, the photon interacts with the atom as a whole. It is completely absorbed and a bound electron is ejected from the atom, with an energy corresponding to the energy of the incident photon minus the binding energy of the electron in its shell. This ejected electron is called
Figure 2.2: Cross-sections of photon interaction in NaI, as a function of energy [44]. The two component cross-sections $\sigma_{a/p}$ and $\sigma_{s/p}$ should be summed in order to find the actual cross-section of the Compton scattering process.
the photoelectron. It can carry an important fraction of the photon energy – depending of course on how large that energy was – and it will likely be able to ionize other atoms. This corresponds to the mechanism of indirect ionization that we have mentioned before. The cross-section of photoelectric absorption as a function of the photon energy shows one or several discontinuities, called “absorption edges”, which correspond to the various shells for the atomic electrons. The photoelectric absorption leaves the original atom ionized and with a vacancy in one of its shells. This will result in a capture of a free electron and/or a rearrangement of electrons from other shells of the atom. This rearrangement will be accompanied by the emission of some fluorescence photons (typically X-rays) or else a so-called Auger electron, in order to carry away the excitation energy [2].

In scattering, a photon does not necessarily lose energy: the scattering can be coherent or incoherent. In coherent scattering, also called Rayleigh scattering, the photon does not transfer energy and is scattered by the atom as a whole, in the sense that all atomic electrons participate to the process in a coherent manner [4]. In Compton scattering, which is the incoherent process, the photon interacts with one atomic electron, whose binding energy is negligible with respect to the photon energy. The photon transfers to the electron a given fraction of its energy depending on the photon scattering
angle $\theta$, according to the following formula [4]:

$$E_{tr} = E \frac{E}{m_e c^2} \left(1 - \cos \theta\right) \frac{1}{1 + \frac{E}{m_e c^2} \left(1 - \cos \theta\right)}$$

(2.9)

where $m_e$ is the electron mass, $E$ is the initial energy of the photon and $E_{tr}$ is the transferred energy, whose maximum is reached for $\theta = 180^\circ$.

Pair production is only possible when the energy of the photon is higher than 1.022 MeV. The interaction takes place in the electric field of a nucleus and replaces the photon by an electron-positron pair. After slowing down, the positron will annihilate with an electron, so that also two secondary photons are produced due to the pair production.

### 2.1.3 Ionization in gas detectors

So far, we have mentioned as mechanism of ionization the process in which a charged particle or a photon interacts with an atomic electron which is ejected from its atom. When ion-electron pairs are created directly by the incoming radiation itself, this process is referred to as primary ionization. The electrons liberated in these ionizing collisions are called secondary electrons. The maximum energy $E_{\text{max}}$ that these can assume depends on the ionization mechanism by which they were created (cf. sections 2.1.1 and 2.1.2). Secondary electrons whose energy is larger than the first ionization potential of the medium will themselves ionize other atoms and are called “$\delta$-rays”. If the energy of the newly liberated electrons is also high enough, again other atoms can be ionized, and so on, until the threshold of the first ionization potential is reached. All the extra ion-electron pairs that were created after the primary ionization, are known as secondary ionization. In most gases used in gas detectors, the ionization energy for the least tightly bound electron shells typically lies between 10 and 25 eV [2]. Argon, which is often used in gas detectors, has for example a first ionization potential of 15.7 eV.

The direction of motion of $\delta$-rays is quickly randomized due to multiple scattering in the medium [5]. Their practical range will therefore be about two or three times smaller than their total range along their trajectory (that can be calculated by integration of the stopping power formula) [5]. This practical range sets an intrinsic limit to the position accuracy of gas detectors in which
the position of the primary event is inferred from the center of gravity of the
detected charge. In a single gas counter operating at atmospheric pressure,
the position accuracy is limited to somewhere between 20 and 30 μm [5].

In gas detectors, two other types of ionization mechanisms, that we have
not mentioned yet, can also occur [4]:

1. In a mixture of a noble gas and an additive molecular gas, or of two dif-
ferent noble gases, when atoms of the principal component are excited
in a metastable state, which by definition makes them unable to return
immediately to their ground state by photon-emission, they deexcite
through a collision with an additive atom which gets ionized due to the
transferred energy. This is called the Penning effect.
2. In noble gases, it can also happen that a positive ion interacts with an
atom of the same type to form a molecular ion and a free electron.

Besides these ionization mechanisms, simple charge transfers from a positive
ion to a neutral molecule will also happen. In gas mixtures, this process is
particularly significant because there will be a global tendency to transfer
the net positive charge to the species with the lowest ionization potential,
since energy is liberated in these transfers [2].

A very important property regarding ionizing radiation in gases, is the re-
lation between the total deposited energy $E_{dep}$ and the average total number
of electron-ion pairs $n_T$ produced in the gas volume, regardless the direct or
indirect ionization mechanisms involved. This relation is usually expressed
as follows [5]:

$$E_{dep} = W n_T,$$

(2.10)

where $W$ is the average energy per electron-ion pair produced. The $W$-value
is of course substantially larger than the mean ionization potential of the gas,
since there are other mechanisms than ionization through which the detected
particle loses energy in the gas. The important point is that experimental
data show that the $W$-value is not a strong function of the gas species, nor of
the radiation type and its energy. For a given radiation type and gas species,
it can for example be assumed that $n_T$ is proportional to $E_{dep}$. The $W$-value
is typically around 25-35 eV per electron-ion pair (e.g. for argon, $W = 26$ eV
per electron-ion pair) [2].

For gas mixtures, one can compute $n_T$ separately for each gas species (as if
the latter was filling the volume alone) and then make the average of these values weighted by the volume fractions of the different gas species. This rule can also be used for the average number of primary electron-ion pairs \(n_P\) created in a gas mixture, although no simple expression exists for the \(n_P\)-values of a single gas species and thus experimental data are needed. Sauli shows in reference [5] that if 1 GeV/c protons cross 1 cm of pure argon at normal conditions, they will produce in average 29 primary ionizations, from which about 10 collisions liberate a \(\delta\)-ray. Note that if a molecular additive is added, the average number of primary ionizations (and also the average total number of ionizations) will be somewhat larger, because a fraction of the excitation energy is recovered for ionization through the Penning effect.

As primary ionization is a consequence of a small number of independent events, it is characterized by a Poisson distribution. The probability of having \(k\) primary ionizations due to one detected particle is:

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

(2.11)

Theoretically, the maximum possible efficiency of a detector corresponds to a situation in which only one primary ionization would be sufficient to detect a particle. This efficiency is thus:

\[
\epsilon = 1 - P^{n_P}_0 = 1 - e^{-n_P}.
\]  

(2.12)

2.1.4 Neutralization in gas detectors

To detect an ionizing particle with a gas detector, it is of course not sufficient just to create electron-ion pairs; these charges should also remain in a free state until they are collected at the electrodes. There are however several ways in which the free charges can get neutralized before being collected [5]. Free electrons can be lost through:

- recombination with a positive ion.
- attachment to an electronegative molecule, which results in a negative ion.
- absorption in the walls of the detector.

Positive ions can disappear through:

- recombination with a free electron.
• recombination with a negative ion.
• neutralization at the walls of the detector, from which they extract electrons.

Noble gases, hydrogen, nitrogen and hydrocarbon gases have a negative electron affinity and are used as the main gas component in different kinds of gas detectors because the probability of electron attachment is nearly zero for their molecules [2]. Noble gases are often chosen for charged particle gas detectors. Electronegative molecules, like \( O_2 \) and \( H_2O \), are however avoided because they can significantly reduce the detected pulse height in proportional counters. Indeed, a 1% pollution of air in argon will remove about 33% of the electrons per cm of drift [5].

As far as recombination between positive and negative ions is concerned, the rate of recombination is proportional to the product of the concentrations of the positive and the negative ions respectively, and it is usually several orders of magnitude larger than the rate of recombination between positive ions and free electrons [2].

Columnar recombination, which occurs near the track of the ionizing particle, has a higher rate in the case of densely ionizing particles, such as \( \alpha \)-particles, compared with fast electrons that deposit their energy over a longer track. This recombination does not increase with the flux of detected particles, as opposed to volume recombination, which takes place outside the immediate location of the track [2].

2.1.5 Diffusion of ions and free electrons without electric field

The ions and free electrons produced in a gas have a tendency to diffuse away from the regions of high density in which they were created. A point-like collection of ions or electrons will spread spatially into a three-dimensional Gaussian distribution whose standard deviation \( \sigma \) increases with the elapsed time \( t \) as

\[
\sigma(r) = \sqrt{6D}t, \tag{2.13}
\]

where \( r \) is the radial distance.

The diffusion coefficient \( D \) can be calculated in simple cases from kinetic gas theory [5]. It increases with the average velocity, which is larger for the
electrons than for the ions, due to the smaller mass of the former. In fact, as
the ions and the electrons lose their energy in multiple collisions, they quickly
reach thermal equilibrium, in which their velocities assume the Maxwellian
distribution. The average diffusion velocity is then given by [4]:

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

(2.14)

where \( k \) is Boltzmann’s constant, \( T \) the temperature and \( m \) the mass of the
particle. At room temperature, the average electron speeds are typically
around 10 cm/\( \mu \)s while the positive ion speeds are three orders of magnitude
smaller [5]. The diffusion process is thus much more pronounced for free
electrons than for ions. In argon, diffusion coefficients of electrons are of the
order of 200-300 cm\(^2\)/s [46].

2.1.6 Drift and diffusion of ions and free electrons in
an electric field

In a gas detector, an electric field is applied throughout the gas. The net
motion of free electrons and positive ions will then consist of a superposition
of the random thermal motion of diffusion with a (slower) net drift motion
along the electric fieldlines – in the direction of the conventional electric
field for the positive ions and in the opposite direction for free electrons
and negative ions. The acceleration of the charges in the electric field is
regularly interrupted by collisions with gas molecules and this limits the
velocity component parallel to the field lines. The average maximum value
attained for this velocity component is called the drift velocity and can be
expressed as follows [4]:

\[ w = \mu \frac{E}{p}, \]  

(2.15)

where \( \mu \) is a function called mobility, \( E \) is the electric field intensity and \( p \) is
the gas pressure. The ratio \( E/p \) is called the reduced electric field. For ions,
the mobility is fairly constant over wide ranges of \( E \) and \( p \), so the ion drift
velocity can be considered proportional to the electric field intensity at a given
pressure. For electrons, however, the dependence of the drift velocity on the
electric field intensity is more complex. In many gases, the electron mobility
globally tends to increase with increasing ratio \( \frac{E}{p} \) [2]. In some hydrocarbons
and argon mixtures, instead, a saturation effect is observed, whereafter the electron mobility might even slightly decrease [2]. Because electrons have a much smaller mass, they can increase their velocity in between collisions significantly more than ions, so roughly speaking, their mobility is a thousand times greater than for ions. In gas detectors, the collection time of ions is therefore usually three orders of magnitude greater than for electrons [2]. At 1 atm and for an electric field on the order of 1 kV/cm, a typical electron drift velocity is a few cm/\mu s [4]. In electric fields of 2-3 kV/cm, which are typical drift fields of GEM detectors (cf. section 2.3.1), the electron drift velocity is about 6 cm/\mu s [46].

2.1.7 Gas multiplication

Gas multiplication is a very important feature of many gas detectors, because it provides an amplification of the total ionization, which most of the time is indispensable to get a detectable electrical signal. The amplification is realized by applying an electric field strong enough to increase the usual secondary ionization processes described in section 2.1.3.

For an electron whose energy is larger than the first ionization potential of the gas, the probability to ionize a molecule depends on this electron’s energy. This probability increases up to circa 100 eV for most gases, whereafter the probability tends to decrease [5]. As the electric field increases above a few kV/cm, the increase of the electron drift velocity is such that more and more liberated electrons have a high probability to produce an ionization in their collisions and an avalanche of ionizations occurs. In the same category of electric fields, the ion drift velocity is however not sufficient to make ions also the cause of such an avalanche process.

The mean free path for ionization is the average distance an electron has to travel before it produces an ionization. The first Townsend coefficient \( \alpha \) is defined as the inverse of the mean free path for ionization and corresponds to the mean number of electron-ion pairs that the electron produces per unit length of drift. The dependence of \( \alpha \) (divided by the gas pressure) on the reduced electric field is shown for several noble gases on Figure 2.4.

In a uniform electric field, a liberated electron will produce an electron-ion pair after a mean free path \( 1/\alpha \). Then two electrons will be drifting in the electric field and, again after one mean free path, they will produce two other electron-ion pairs, and so on. Therefore, if at a given position there are \( n \) free
electrons, after a path $dx$, we know that $dn = n_0 dx$ new electrons will have been produced in average. In a non-uniform electric field, in which $\alpha$ is a function of the abscissa $x$, and starting from $n_0$ initial electron-ion pairs at $x = x_0$, we obtain for the mean number of electron-ion pairs $n(x)$:

$$n(x) = n_0 \exp \left[ \int_{x_0}^{x} \alpha(\chi) d\chi \right] = n_0 G,$$

where $G$ is the gas gain (or multiplication factor).

In a parallel-plate chamber, the spatial distribution of the created charges of an avalanche has a drop-like shape. This drop has a net movement towards the anode while its tail is also getting longer, as schematized on Figure 2.5. All the electrons are situated at the front of the drop while the long tail is due to the positive ions, as can be understood from the large difference in drift velocity between electrons and ions. In a wire-chamber, the avalanche eventually surrounds the anode wire because its diameter is small with respect to the lateral diffusion of the charges. The electrons are fastly collected and a cloud of positive ions is left, which will slowly migrate towards the cathode. This process is schematically shown in Figure 2.6.
2.1.8 Discharges in gas detectors

In the gas multiplication process, the gain $G$ cannot be increased at will. At a given electric field, secondary avalanches (not initiated by the detected particle) start to appear nearby the first avalanche formed in the detector in a way that the proportionality between the primary ionization and the collected charge is lost. As the electron drift velocity increases, so does (at least to a certain point) the probability of ionization but also of excitation. As more and more molecules are excited, an increasing number of deexcitation photons are emitted. Also the higher recombination rate is responsible for a larger production of photons. Some of these photons can ionize gas molecules in the vicinity of the primary avalanche and induce secondary avalanches. These are drawn towards the primary avalanche because the space charge is sufficiently large to disturb the external electric field (basically, the free electrons of a secondary avalanche are attracted by the primary positive ion tail). This leads to the formation of a streamer (cf. Figure 2.7). Photons can also ionize atoms of the electrodes. Electrons ejected in this manner from the cathode will also generate secondary avalanches, especially when the positive tail of
Figure 2.7: Photon-mediated backwards formation of a streamer [11]. The cathode and anode are respectively at the top and bottom of the image. The primary avalanche is the lower one.

Figure 2.8: Cloud chamber photographs of the streamer and spark formation: (a) two avalanches near the anode, (b) and (c) evolution into a streamer, (d) and (e) establishment of the plasma channel (spark) [47].

The streamer is coming closer and creates an increased electric field nearby the cathode. When the tail of the streamer touches the cathode, its head has already reached the anode too, so that a plasma channel is established, giving rise to a spark. This is the fast breakdown process that can typically occur in gas detectors which are operated nearly at the atmospheric pressure. Figure 2.8 is a collection of cloud chamber photographs which show the evolution of the avalanche into a streamer and finally a spark. The transition from an avalanche into a streamer usually happens when the charge density in the avalanche leads to a space charge field comparable to the external field, which in practice corresponds to about $10^7$-$10^8$ electron-ion pairs in an avalanche, known as the Raether limit [5]. Gas detectors can generally not be operated at gains above $10^6$, because the statistical distributions of the energy of the electrons implies that some avalanches will already have a too large charge...
density at such an average multiplication factor.

### 2.1.9 Basic operating modes of gas detectors

Depending on the applied voltage, gas detectors can be operated in various modes. The detector geometry determines which operating modes are possible. For example, gas counters with thin anode wires present the main following operating modes [2]:

1. **The ionization mode**: a mode in which the applied voltage is sufficient to prevent recombination for all of the radiation-produced electron-ion pairs, so that those are fully collected, but without any charge multiplication yet. Since the minimum voltage for full collection is lower than the minimum voltage at which avalanches start to appear, this region corresponds to a plateau in the graph of the collected charge vs the applied voltage (cf. Figure 2.9).

2. **The proportional mode**: from a certain voltage threshold, the electric field intensity (which decreases radially from an anode wire to the cathode) becomes large enough to create avalanches inside a small cylindrical region around the anode-wires. All radiation-produced electrons travel more or less the same distance in this charge amplifying region and therefore the amplitude of the generated electric pulse is proportional to the average total ionization $n_T$ produced by the detected particle, since each of its free electrons induces an avalanche of same gain. This gain also increases linearly with the applied voltage, as can be deduced from Figure 2.9.

3. **The limited proportionality mode**: as the voltage is further increased, the number of electron-ion pairs inside the avalanches becomes so large that the proportionality between the signal amplitude and $n_T$ is gradually lost because of the increasing space charge effects, mainly due to the accumulation in the amplification region of the slow drifting positive ions, which modify the total electric field. On Figure 2.9, we can see that the curves of the detected $\alpha$- and $\beta$-particles are progressively joining each other, although their $n_T$ values are different. A saturation mode is thus eventually reached, in which the signal is independent of the original ionization. The collected charge per event can then still be increased by a process similar to the streamer formation discussed in section 2.1.8, with photon-induced secondary avalanches. However, the secondary avalanches only spread along the anode wire, and do not
Figure 2.9: The collected charge as a function of the applied voltage in thin-wire gas counters and the corresponding operating modes of these detectors [48].

propagate towards the cathode like in streamers, because the electric field drops with the distance to the thin anode.

4. The Geiger-Müller mode: at higher voltages, a new plateau in the graph of the collected charge is reached. In this case, a maximum number of secondary avalanches, covering the whole length of the anode wire, is attained because the global space-charge build-up reduces the electric field intensity enough to stop charge multiplication around the anode.

5. The permanent discharge region: further increasing the voltage will lead to the undesired situation in which discharges occur also in the absence of primary ionization.

To stress the importance of the detector geometry with respect to its gas multiplication and discharge properties, let us for example mention that no proportional mode exists for simple parallel-plate chambers, because of their uniform electric field. Indeed, when the field intensity is constant, an avalanche can be initiated anywhere in the gas volume, provided that the applied voltage is sufficiently high (e.g. in Parallel-Plate Avalanche Chambers). Since the first Townsend coefficient $\alpha$ is also constant, the avalanche
gain (cf. Equation (2.16)) will be proportional to the distance between the point where the initial free electron was created and the anode, instead of being constant as in the proportional mode. Moreover, we explained in section 2.1.8 that in parallel-plate chambers, streamers can reach the cathode and evolve into spark discharges, whereas in wire chambers we rather observe the above described Geiger discharges.

2.2 The single-GEM detector

The simplest gas detector of the Gas Electron Multiplier (GEM) technology is the single-GEM chamber, which consists of one GEM foil to which a tension is applied and which is sandwiched between two flat parallel electrodes, where the anode is a read-out plane made up of strips or pads. A schematic cross-section view of a single-GEM detector is given in Figure 2.10. A GEM foil typically consists of a 50 $\mu$m thick insulating Kapton foil cladded on both sides with a 3 to 5 $\mu$m copper layer and very densely perforated with thiny holes in a triangular pattern of pitch 140 $\mu$m (cf. Figure 2.11). The holes are usually biconical (created with the double-mask technique, cf. 2.4.1), with an internal and an external diameter of respectively 50 $\mu$m and 70 $\mu$m. Because a voltage is applied between the two copper layers of the GEM foil, a gas multiplication avalanche occurs within the holes, which act like independent proportional counters when the detector is correctly operated. The gap between the cathode and the GEM foil is called the drift gap. The role of the corresponding electric field, called the drift field, is to collect the ionization electrons inside the GEM holes. In the induction gap, located between the GEM foil and the anode, the induction field extracts the avalanche electrons from the GEM holes and makes them to drift towards the anode, so that a signal is induced on the nearby read-out strips (or pads). Examples of read-out plane geometries are shown in Figure 2.13.

2.2.1 Operation of a single-GEM detector

Drift gaps of single-GEM detectors are usually 3 mm thick and their drift fields are around 2 kV/cm [12] which thus corresponds to an applied voltage of around 600 V. Further increasing the thickness of the drift gap does not increase the detection efficiency and could even increase the ageing rate as well as the pile-up effects at very high hit rates [12].
Figure 2.10: Schematic cross-section view of a single-GEM detector [12]. $E_D$ and $E_I$ are the drift and the induction fields, $g_D$ and $g_I$ are the drift and induction gaps, and $V_{GEM}$ is the voltage difference applied between the copper layers of the GEM foil.

Figure 2.11: Typical geometry features of GEM foils with biconical holes [49]. The pitch is generally $P = 140 \mu m$, the internal diameter $d = 50 \mu m$ and the external diameter $D = 70 \mu m$.

Figure 2.12: Electron microscope picture of a standard-design GEM foil [50].
When a voltage of about 200 V is applied on a GEM foil, the electric field inside its holes reaches \(\approx 40 \text{ kV/cm}\) and charge multiplication occurs [46]. In operation, this voltage is typically between 400 and 500 V, creating an electric field up to 100 kV/cm [52].

The induction gap is generally 1 to 2 mm thick with an induction field of about 5 kV/cm [12] (induction voltage between 500 and 1000 V). Reducing the thickness of the induction gap has the advantage to increase the GEM signal amplitude, which is proportional to the ratio between the electron drift velocity and the thickness of the induction gap, but it requires a higher mechanical tolerance in order to assure the operation stability of the detector (the discharge probability is for example increased) [12].

Thanks to the electric field configuration inside a single-GEM detector (cf. Figure 2.14), most ionization electrons created in the drift gap are collected in the GEM holes and only a small fraction (about 10\%) is lost on the low potential electrode of the GEM foil due to diffusion [12]. However, usually only 50 to 60\% of the multiplication electrons inside a GEM hole eventually drifts towards the anode [12][51], because a rather large fraction of these electrons follow field lines that bring them towards the high potential electrode of the GEM foil. Some multiplication electrons are also lost inside the GEM holes because the Kapton, being a dielectric, gets polarized in the electric field and thus some field lines enter in it, wherefore electrons are deposited on its surface, especially in the narrow central region of the hole. This deposited charge builds up during the irradiation of the detector, leading to an increased electric field intensity at the center of the hole and thus a progressive gain rise (up to \(\approx 30\%\)). This effect is called charging up
and can be reduced by using a cylindrical hole geometry [46], which can be approximated by the most recent single-mask technique (cf. section 2.4.1).

As for the multiplication ions, most of them are collected on the low potential electrode of the GEM foil [49]. Indeed, the charge multiplication inside a GEM hole is denser nearby its walls due to a higher field line density. A great majority of the electron-ion pairs is thus created along field lines that end up on the copper layers of the GEM foil. Since for ions the diffusion is much lower than for electrons, few of them reach the central zone of the hole and can follow field lines that lead them to the cathode. This is an excellent feature that allows a very fast signal, the pulse being essentially induced by the drift of the electrons which have a high mobility. In a Multi-Wire Proportional Chamber (MWPC), instead, the signal is mainly induced by the drift of the ions and is therefore much slower [5]. A GEM detector also has a very thin amplification region, leading to a very short signal rise-time, typically of a few nanoseconds [51]. GEM detectors possess a high rate capability, that can go up to a few hundred millions of hits per second and per cm$^2$ [57], thanks to the fact that it only takes about a few microseconds to clear the amplification regions (i.e. the GEM holes) from ions [51], unlike the MWPC whose signal is affected by the typical long ion tail.

2.2.2 Effective gain of a single-GEM detector

The intrinsic (or absolute) gain $G_i$ of a GEM foil corresponds to the ratio of the free electrons that are collected in the GEM holes over the total number of electrons produced by avalanche multiplication inside these holes. It depends on the voltage $V_{GEM}$ applied to the GEM foil in the following way [12]:

$$G_i \sim e^{<\alpha> V_{GEM}},$$

where $<\alpha>$ is the average first Townsend coefficient along the electron path through the hole. As we explained in section 2.1.8, the gain of a gas detector is limited by the appearance of discharges. When the total charge per avalanche reaches the Raether limit of $10^7-10^8$ electron-ion pairs, photon-induced secondary avalanches lead to the formation of a streamer. In a single-GEM detector, discharges remain in most cases localized in the GEM holes, but sometimes discharges propagate towards the read-out plane, which can lead to the destruction of the front end electronics. The probability of the
transition from localized to propagated discharge increases with the strength of the induction field [46].

The effective gain $G_e$ of a single-GEM detector, which is determined by the magnitude of the anode current, is lower than the intrinsic gain $G_i$ due to the dispersive effects that decrease the number of electrons transferred to the anode. The effective and intrinsic gains are correlated through the following relation [12]:

$$G_e = G_i T = G_i \epsilon_{\text{coll}} f_{\text{extr}},$$

(2.18)

where $T \in [0, 1]$ is called the electron transparency, $\epsilon_{\text{coll}}$ is the collection efficiency and $f_{\text{extr}}$ is the extraction fraction. The collection efficiency is defined as the ratio of the number of electrons collected in the GEM holes over the number of electrons produced in the drift gap. It can be improved by increasing the drift field so that diffusion losses are reduced on the low potential electrode of the GEM foil and on the surfaces of GEM holes before multiplication has started. The best collection efficiencies are obtained with a drift field between 1 and 3 kV/cm, because at higher values a defocusing effect of the field lines directs the electron drift velocity towards the low potential electrode of the GEM foil [12]. The extraction fraction is the ratio
of the number of electrons extracted from the holes over the number of electrons produced inside the holes. Increasing the induction field improves the extraction fraction, but above 5 kV/cm propagating discharges are likely to occur. The maximum effective gain achievable with a single-GEM detector is of the order of $10^3$ [12].

2.3 The triple-GEM detector

2.3.1 Operation of a triple-GEM detector

In a triple-GEM detector, three GEM foils are cascaded in between the cathode and the read-out anode, as shown in Figure 2.15. The drift field, located between the cathode and the first GEM foil (in the drift gap), has the same function as in a single-GEM detector, i.e. the collection of the free electrons induced by the detected particle. The gaps in between two consecutive GEM foils are called transfer regions and act respectively as an extracting induction region for the GEM foil with the lower potentials and a collecting drift region for the GEM foil with higher potentials. The third GEM foil (with the highest potentials) is separated from the read-out anode by an induction field, in which the electron drift induces the signal like in a single-GEM detector.
For the drift and induction gaps and fields of a triple-GEM detector, the same considerations as for single-GEM detectors apply (cf. section 2.2). The two transfer gaps play a crucial role, because it has been demonstrated that two GEM foils in contact provide the same performances as a single GEM [55]. Their thickness is usually 2 mm, although the first transfer gap (located between the first and the second foils as defined in the previous paragraph) is sometimes reduced to 1 mm to improve the time resolution of the detector, but at the expense of a higher discharge probability. If the distance between two GEM foils is larger, the electron cloud diffuses more before reaching the following GEM foil, which reduces the number of electrons per avalanche in the holes of this foil. The Raether limit (cf. section 2.1.8) is thus less easily reached, yielding a lower discharge probability. The time resolution however is related to the so-called bi-GEM effect in which the main signal is preceded by a small amplitude pulse, in advance of 10 to 20 ns [12]. This effect results from the fact that the detected particle can produce primary ionization in all of the gaps. Only the primary ionization induced in the first transfer gap, and thus amplified by two GEM foils, is responsible for a preceding pulse large enough to be discriminated by the front-end electronics. Reducing this gap thickness not only reduces the probability of this preceding pulse but also the advance it has on the main signal. Increasing the voltage applied to the first GEM foil with respect to the second also helps to reduce the bi-GEM effect.

The transfer fields in a triple-GEM detector are usually between 3 and 4 kV/cm [12]. The value must be chosen in order to maximize both the extraction fraction of the GEM foil with lower potentials and the collection efficiency of the GEM foil with higher potentials. At low values of the transfer field, the former one will be too small, whereas at high field intensities, the latter one will be reduced by a high defocusing effect (cf. section 2.2.2).

### 2.3.2 Effective gain of a triple-GEM detector

For a triple-GEM detector, the intrinsic gain $G_i$ is defined as the product of the intrinsic gains of the three GEM foils (cf. section 2.2.2). Therefore, $G_i$ is an exponential of the sum of the three GEM voltages $V_{GEM_1}$, $V_{GEM_2}$ and $V_{GEM_3}$:

$$G_i \sim e^{<\alpha>(V_{GEM_1} + V_{GEM_2} + V_{GEM_3})}. \quad (2.19)$$
The effective gain $G_e$ of a triple-GEM detector is the product of the effective gains of the three GEM foils and is thus given by [12]:

$$
G_e = G_i T_{tot} = G_i \prod_{k=1}^{3} \epsilon_{coll_k} f_{extr_k},
$$

(2.20)

where $\epsilon_{coll_k}$ and $f_{extr_k}$ are the collection efficiency and the electron fraction of the $k^{th}$ GEM foil and $T_{tot}$ is the total electron transparency of the detector.

When increasing the effective gain, the probability of discharges of course increases. For multi-GEM detectors, discharges will first appear in the last multiplication step because it has the largest total number of electrons per avalanche. Since the effective gain only depends on the GEM voltages through their sum, it is thus useful to unbalance these voltages in order to reduce the gain of the last multiplication step. It has been shown that the optimal configuration of the GEM voltages is [56]:

$$
V_{GEM_1} \gg V_{GEM_2} \geq V_{GEM_3}.
$$

(2.21)

The advantage of multi-GEM detectors over single-GEM detectors lies in the fact that higher maximum effective gains can be achieved before the appearance of discharges, as shown in Figure 2.16. Indeed, thanks to the diffusion in the transfer gaps, the same total gain is achieved but by steps in which the charge density per hole is reduced and thus the Raether limit is less easily reached for the several avalanches. The maximum effective gain for triple-GEM detectors are between $10^4$ and $10^5$ [12]. Typically, a sufficient effective gain is obtained with lower GEM foil voltages than in single-GEM detectors (they are usually of 300-350 V in triple-GEM detectors) [59].

2.4 Particularities of GEM foils

2.4.1 Manufacturing techniques of GEM foils

Conventional photolithography methods are used for the manufacturing of GEM foils. The double-mask method has been the standard production method until today, but recently the single-mask method has been considered a mature manufacturing process as well [53].
Figure 2.16: Discharge probability as a function of the gas gain for single, double and triple GEM detectors with an Ar/CO$_2$ (70/30) gas mixture [58].

Standard GEM foils produced with the double-mask method have biconical holes as the result of a compromise between production yield and safe operation of the detector [12]. The process, schematized on Figure 2.17, starts with the application of a solid photoresist coating on both sides of the raw material (usually a 50 $\mu$m thick Kapton layer with 5 $\mu$m copper cladding on both sides), which is then placed in between two identical masks possessing the GEM hole pattern. This pattern is engraved in the copper layers by exposure to UV rays, whereafter the unprotected Kapton is chemically etched from both sides. The critical aspect in this process is the alignment of the two masks for which errors should be kept below 10 $\mu$m [53], to avoid lower gains and significant charging up in slanted holes. Since both the raw material and the two masks are flexible, the manual alignment procedure becomes very difficult when the foil area exceeds about 45 x 45 cm$^2$ [43].

Because of the increasing demand for large area GEM foils, a new manufacturing technique based on single-mask photolithography and the splicing of foils has been developed [53]. In this method, illustrated in Figure 2.18, the hole pattern is transferred to only one copper layer of the foil, removing any need for alignment. Conical holes are then etched into the Kapton from that side. The second copper layer is pierced by immersing the foil completely into an acid solution, so that the copper is attacked from both sides only in the holes of the Kapton, which acts as a mask. An electrochemical active corrosion protection is used to avoid rims around the holes in the first
copper layer. The steepness of the conical holes is increased with a moderate overetching of the second copper layer followed by a $\approx 30$ s etching of the Kapton, so that the obtained hole shape is almost cylindrical. To make GEM foils that are larger than the available rolls of raw material, several foils can be spliced together by means of two 2 mm wide Kapton cover layers, one on each side of the GEMs. Each cover layer is carefully aligned along the foils’ edges and then fixed in place by applying pressure at $240^\circ$C so that the resulting seam is flat, regular, mechanically and dielectrically strong.
2.4.2 Influence of the diameter, shape and pitch of GEM holes

Reducing the GEM hole diameter down to $\approx 70 \, \mu m$ allows to achieve higher gains thanks to a higher field line density inside the holes. However, at equal gas mixture and electric fields conditions, a gain saturation effect is observed for hole diameters below $\approx 70 \, \mu m$, as increasing losses of electrons to the high potential GEM foil electrode compensate the larger electron multiplication [12]. The hole pitch does not play a role in the intrinsic gain, but for a given GEM hole diameter, the achieved collection efficiency is increased using a smaller pitch [12]. The hole shape affects the charging-up, as discussed in section 2.2.1. The cylindrical geometry is the one that reduces the most the undesirable short-term gain instability related to charging-up.

2.4.3 Sectorization of GEM foils

When operating GEM detectors, the discharge probability in GEM detectors can never be assumed to be zero and it is therefore necessary to ensure that, in case of accidental sparking, no permanent damages are caused to the detector structures and electronics [55]. Especially propagated discharges, which reach the anode read-out plane, should be strictly avoided. The maximum available energy for a discharge should also be limited. For these reasons, GEM foils have one copper layer that is subdivided in electrically separated sectors. This allows to [46]:

1. reduce the probability of the transition from a localized discharge into a propagated discharge,
2. reduce the lateral spread of propagated discharges,
3. reduce the energy of a discharge. This energy depends on the capacitance of the GEM foil, for localized discharges, and on the capacitance between the GEM foil and the read-out plane, for propagated discharges. Sectorizing one of the electrodes of the foil reduces these capacitances.
2.5 Fill-gases for GEM detectors

In general, the choice of a fill-gas depends on the specific requirements of the gas detector (e.g. low operating voltage, high stability, high gain). Noble gases are very often chosen as a main component because, thanks to their electronegativity, gas multiplication occurs at lower fields than in complex molecular gases [5]. Especially argon is often used in GEM detectors, since its high atomic number \((Z = 18)\) leads to a high value of the first Townsend coefficient (i.e. a larger average number of electron-ion pairs produced per unit length of path of a charged particle). Xenon and krypton have even higher atomic numbers but are too expensive.

As GEM detectors are operated in a proportional mode, an additive called the quencher is added in order to prevent discharges. Indeed, due to the statistical fluctuations of the primary ionization and the gas multiplication factor, it is possible that at least one avalanche exceeds the Raether limit and evolves into a streamer. The quencher, for a detector operated in the proportional mode, is a polyatomic gas that possesses a large amount of non-radiative rotational and vibrational excited states [5]. It can absorb photons over a wide energy range and dissipate the absorbed energy by molecular collisions or by dissociation of the excited molecules. The quencher is selected in order to absorb the emitted photons which are responsible of the secondary avalanches inside a streamer. Its use is essential to avoid the transition into a permanent discharge mode when high gains are sought. The larger the number of atoms in the molecules, the more non-radiative excited states are accessible and the more efficient is the quencher. Isobutane has been often used, but radiation-induced chemical reactions of such an organic gas produce polymeric molecules which are deposited on the detector electrodes and lead to fast aging. Moreover, organic gases are also flammable and toxic. For these reasons, carbon dioxide has now become a standard quencher in GEM detectors, although its quenching efficiency is significantly lower. The use of \(\text{CO}_2\) results in a limit of the order of \(10^4\) for the triple-GEM effective gain and the necessity to use rather high operating voltages to achieve sufficiently high gains [46]. When compared to \(\text{Ar/CO}_2\) mixtures with a smaller \(\text{CO}_2\) content, a mixture of 70% (vol.) \(\text{Ar}\) and 30% (vol.) \(\text{CO}_2\) provides a good protection against discharges and reduced gain modifications with GEM voltage variation [46].
2.6 The main characteristics of GEM detectors

When compared to wire chambers, the triple-GEM detectors, being micro-pattern detectors, can achieve higher effective gains (of the order of $10^5$), have faster signals (with rise-times of 10 to 20 ns) and higher rate capabilities (up to a few 100 MHz/cm$^2$). They also have an excellent intrinsic spatial resolution of $\approx 40 \mu$m RMS and a two-track resolution (cluster size) of $\approx 500 \mu$m FWHM [57]. Table 2.1 gives an overview of the order of magnitudes of the maximum achievable gain and hit rate, as well as the spatial and time resolution for different gaseous trackers. Also the spatial and time resolution of silicon microstrip trackers is given for comparison in Table 2.1.

Unlike for Micro-Strip Gas Chambers (MSGC), the effective gain (and thus the efficiency) of GEM detectors does not decrease with increasing hit rates (at least until $\approx 100$ MHz/cm$^2$). With respect to other micro-pattern gas detectors, the GEM technology has also the advantage to be more flexible in the read-out geometry because the amplification steps are physically distinct from the read-out plane. For the same reason, it has a greater re-usability as well. Moreover, at equal gains, the probability of discharges is lower in triple-GEM than in MicroMeGas detectors.

Technically speaking, silicon microstrip detectors are actually better trackers than GEM detectors, but their tile size is limited to $\approx 12 \times 12$ cm$^2$ and they are very expensive [63]. GEM foils, however, can be produced in large areas at much lower cost. A prototype triple-GEM detector of $\approx 2000$ cm$^2$ active area has even been built recently at CERN (cf. [53]). GEM foils are also good radiation tolerant devices, while silicon detectors suffer noticeable aging in intense radiation fields [64].
<table>
<thead>
<tr>
<th>Detector</th>
<th>Maximum gain</th>
<th>Maximum hit rate [MHz/cm²]</th>
<th>Spatial resolution [μm]</th>
<th>Time resolution [ns] RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon microstrip</td>
<td>/</td>
<td>limited by the electronics</td>
<td>~1-10</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Triple-GEM</td>
<td>~10⁵</td>
<td>~100</td>
<td>~40-50</td>
<td>~10</td>
</tr>
<tr>
<td>MicroMeGas</td>
<td>~10⁵</td>
<td>~100</td>
<td>~40-50</td>
<td>~5</td>
</tr>
<tr>
<td>MSGC</td>
<td>~10⁴</td>
<td>~10</td>
<td>~40-50</td>
<td>~10</td>
</tr>
<tr>
<td>Drift chamber</td>
<td>~10³</td>
<td>~1</td>
<td>~50-150</td>
<td>~5</td>
</tr>
<tr>
<td>MWPC</td>
<td>~10³</td>
<td>~1</td>
<td>~200</td>
<td>~10</td>
</tr>
</tbody>
</table>

Table 2.1: Orders of magnitude of several tracker’s properties compared for silicon microstrip detectors, triple-GEM, MicroMeGas, MSGC, drift chambers and MWPC [12][57][60][61][62].
Chapter 3

GEM chambers for the SBS Front Tracker

3.1 Choice of the GEM technology

The required momentum and angular resolutions of the SBS tracking system (cf. 1.4) correspond approximately to a single hit spatial resolution lower than 100 $\mu$m [24]. The desired 70 $\mu$m spatial resolution [43] can be achieved with silicon trackers, drift chambers and Micro-Pattern Gas Detectors (MPGD). Drift chambers, however, cannot sustain the expected rate of a million hits per second and per cm$^2$ (cf. section 2.6) and generally they are also more sensitive to magnetic fields than the other technologies [24]. As for silicon trackers, we mentioned in section 1.3 that the SBS tracker will possess two 10 x 20 cm$^2$ silicon strip planes close to the target (in order to improve the momentum and angular resolutions), but no silicon detectors will be used for the tracking areas located behind the dipole magnet because such large silicon detectors would be too costly [43]. Among the MPGD, the two most consolidated technologies are the GEM and the MicroMeGas, which are both relatively inexpensive and able to fulfill the main experimental requirements [24]. GEM detectors have been preferred because of their higher flexibility and re-usability (cf. the requirements in section 1.4) and their significantly smaller discharge rate [24].
Figure 3.1: Geometry of the Front Tracker GEM chambers [43]. From left to right: a single 40 x 50 cm$^2$ module, a 40 x 150 cm$^2$ chamber, a read-out board with strips in the U/V directions, and a read-out board with strips in the X/Y directions.

### 3.2 Structure of the GEM chambers

#### 3.2.1 Geometry of a single chamber

Six consecutive identical GEM chambers with an active area of 40 x 150 cm$^2$ are part of the SBS Front Tracker. Each chamber is composed of three adjacent identical 40 x 50 cm$^2$ triple-GEM modules (cf. Figure 3.1). For each module, the front-end electronics is located on four backplanes around the borders. One of them is placed at 90° with respect to the chamber, in the 2 cm gap between two modules, as represented in Figure 3.2. A carbon fiber support frame (in cyan on Figure 3.1) will hold the three modules together in one chamber.

#### 3.2.2 Geometry of a 40 x 50 cm$^2$ triple-GEM module

The SBS 40 x 50 cm$^2$ triple-GEM modules are derived from the COMPASS design (see for example reference [46] and Figure 3.3), but present a larger active area and a greater compactness of the mechanical structure and front-end electronics [24]. The Figure 3.4 gives a schematic view of such a module, which basically consists of:
1. a 3 mm thick Permaglas TE630 frame, without spacers.
2. an entrance foil made of 6 μm mylar which will contain the gas in the chamber. Due to the slight overpressure of the chamber gas with respect to the ambient atmosphere, this entrance foil will be slightly bent.
3. a 2 mm thick Permaglas TE630 frame, without spacers.
4. a drift foil, consisting of 50 μm of Kapton with 3 μm of copper on one side. Note that, if the entrance foil were absent, this drift foil would be deformed by the gas pressure, which would create a distortion of the electric field in between this cathode and the first GEM foil.
5. a 3 mm thick Permaglas TE630 frame with a grid of spacers.
6. a first GEM foil.
7. a 2 mm thick Permaglas TE630 frame with a grid of spacers.
8. a second GEM foil.
9. a 2 mm thick Permaglas TE630 frame with a grid of spacers.
10. a third GEM foil.
11. a 2 mm thick Permaglas TE630 frame with a grid of spacers.
12. a 2D read-out plane.
13. a honeycomb structure, as schematized in Figure 3.5, surrounded by a 6 mm thick Permaglas TE630 frame.

Note that during the construction of a module, the GEM foils are stretched with a specific tool (cf. section 4.2.1) when they are glued to the frames.
CHAPTER 3. GEM CHAMBERS FOR THE SBS FRONT TRACKER

Figure 3.3: Schematic assembly view of the COMPASS design from which the SBS triple-GEM modules are derived [24].

Figure 3.4: Schematic cross-section of a GEM module (adapted from [24]).

Figure 3.5: Composition of the CERN made honeycomb plane [24].
3.2.3 The GEM foils

The GEM foils, which will be produced at CERN with the single-mask technique, consist of a 50 μm Kapton foil with on both sides a copper layer of 3 μm. The copper layer on one side of the GEM foil is made of a single 40 x 50 cm$^2$ sector, while the opposite side, which will be placed at a lower potential, is divided in 20 sectors of 20 x 5 cm$^2$ (in two rows of 10 sectors along the longest borders of the foil).

As we will explain in section 4.2.1, a 1 MΩ protective resistor will be soldered to the pad of each 20 x 5 cm$^2$ sector, as well as to the pad of the 40 x 50 cm$^2$ sector. Figure 3.6 schematically shows the connections for such a protective resistor, along with the seven high voltage (HV) terminals (cf. section 3.4) which are replicated on each GEM foil in order to use the same drawing. Since a GEM foil needs only two HV terminals and the drift foil only one, several unused terminals will be cut on the frame border. The HV terminal of the multi-sector side lies on the single-sector side, while the HV terminal of the single-sector side is located on the multi-sector side. Pass-through holes thus exist for the HV connections.
3.2.4 The mechanical frames

The insulating Permaglas TE630 frames mentioned in section 3.2.2 have a frame width of 8 mm. The 0.3 mm thin spacers inside the frames have to ensure a proper foil spacing and planarity. On the side of the frame which will be in contact with the multi-sector side of a GEM foil, ten slots are foreseen along both of the longest frame borders, in order to solder the protective resistors for the twenty $20 \times 5 \text{ cm}^2$ sectors. On the other side of the frame, an additional slot on one of the shortest frame borders will house the protective resistor of the $40 \times 50 \text{ cm}^2$ sector. The frames also possess inlet and outlet pipes to insure the continuous gas flow in between the several foils. A standard gas mixture such as Ar/CO$_2$ (70/30) will be used, at a pressure slightly above the atmospheric pressure.

The thickness of the drift gap frame is 3 mm, because this guarantees the full efficiency of the detector without producing high aging rates and too many pile-effects [12]. The frames that maintain the transfer gaps and the induction gap have all been given the standard thickness of 2 mm. Although 1 mm thicknesses could be used for the first transfer gap and the induction gap in order to improve respectively the time resolution and the signal amplitude [12], we privileged in both cases a 2 mm thickness in order to simplify the mechanical issues of the frames and to reduce the discharge probability in the detector (which is an important aspect since the SBS trackers will be subjected to high background rates). A 1 mm frame is indeed more delicate and positioning the protective resistors on it is much more difficult. As for the discharge probability, increasing the thickness of a transfer gap allows to spread the charge over a larger amount of GEM foil holes, which reduces the charge density in each hole, and therefore also the probability of initiating a discharge.

The spacer layout of the GEM frames has been modified several times during the development process, the last modifications being a consequence of the activities realized within the scope of this thesis (cf. section 4.1). Originally, this frame design was based on 20 spacer delimited sectors of $\approx10 \times 10 \text{ cm}^2$, but the frame spacers coincided then with the sector separations on the GEM foils and this superposition increases the dead area of the module. The design was modified in order to minimize this undesired overlap and the number of frame sectors was also reduced to 18 (a reduction
compensated by a sufficiently high stretching tension applied to the GEM foils). This design, which is presented in Appendix A, has been the basis for the gas flow simulations described in section 4.1.

### 3.2.5 The 2D read-out planes

Also the read-out foils are inspired from the COMPASS design. They consist of 2 layers of 0.5 μm thick copper strips at 90° from each other (cf. Figure 3.7) and are designed to get equal charge sharing between both read-out coordinates. They are separated by a prepreg foil with the same 0.2 transparency as the top strip layer. The bottom strip layer has a 0.75 transparency and is glued on a G10 120 μm plane. In both layers, the strip pitch is 400 μm, which should not be larger because the transverse size of the electron cloud arriving at the strips is about 500 μm. The read-out foils will be produced at CERN, using chemical etching.

On Figure 3.1, we mentioned the X/Y directions and the U/V directions, which are respectively the directions at 0°/90° and 45°/-45° with respect to the dispersive direction (i.e. along the magnetic field). According to the current Monte Carlo simulations, however, U/V chambers instead of X/Y chambers do not significantly improve the quality of the tracking and eventually it has been decided that all six chambers of the SBS Front Tracker will have read-outs in the X/Y directions.

The 18 front-end cards (cf. section 3.3.1) will be distributed along the four frame sides in a sort of interleaved – comb-like – way (cf. Figure 3.8). JST connectors 73FXZ-RSM1-G-ETF(LF)(SN) with 77 pins (from which 64 are used) will be soldered on the front-end cards, each of which should be connected to 128 read-out strips, through a Flexible Printed Circuit (FPC) that will be bent by 90° on the frame side adjacent to the next chamber module.

### 3.3 Electronics

The read-out electronics chain of one GEM module consists of:

1. Eighteen front-end cards, located on the four custom backplanes around the frame borders of a module. The backplanes provide power and a common ground to the front-end cards. They shield these cards
Figure 3.7: Geometry of the strips on the read-out plane [43].

Figure 3.8: Drawing of a GEM foil superimposed to the read-out plane [65].
electrically and are used to control them and to collect their analog outputs.

2. Two Multi-Purpose Digitizer (MPD) modules, each of them collecting the analog outputs from two backplanes (with respectively 5 and 4 front-end cards) through two HDMI\(^1\) type B cables. These MPD modules also generate the digital signals for the data acquisition computer, as well as the digital triggering signals for the front-end electronics (which are transported by HDMI type A cables). They should be in a radiation safe area at a maximum distance of about 20 m from the front-end cards.

The read-out electronics chain is schematized in Figure 3.9 for a single front-end card.

### 3.3.1 The front-end electronics

Each front-end card (FEC) will house one APV25 chip, which was developed by the Imperial College London for CMS silicon detectors \[^66\] and has already been used for the GEM detectors of the COMPASS and the LHCb experiments. This APV25 chip is an analog pipeline ASIC\(^2\) with serial output. It has 128 channels, each containing a preamplifier and shaper with a 50 ns peaking time, followed by a 192 cells analog memory into which samples are written at a 40 MHz frequency. A sample thus corresponds to the charge collected on a read-out strip during a given fraction of the 25 ns sampling period. After 4 \(\mu s\), which corresponds to 160 samples, the memory cells start to be overwritten. The remaining 32 memory cells are used to store events flagged for read-out by a trigger until the time they can be read out \[^46\]. The time between the event and the arrival of the trigger at the front-end card is called the latency, which is used to define how much time the chip has to go back in its memory to find the signal corresponding to the event.

Two operating modes can be used in the case of GEM detectors \[^46\]:

- the peak mode, in which only a single sample is acquired for a given event (this sample should correspond to the peak of the event signal).
- the multi-mode, in which several (3) consecutive samples are acquired for a single event, so that the time evolution of the event signal can be studied.

---

\(^1\)High-Definition Multimedia Interface

\(^2\)Application Specific Integrated Circuit
In our case, the APV25 chip shapes an event pulse to a width of about 400 ns (which is partially selectable via bias currents). One pulse then requires about 16 clocks to be fully sampled. Figure 3.10 shows a front-end card, with a Flexible Printed Circuit (FPC) and first version FPC connectors (Panasonic YF31 33 ZIF bins, instead of the currently adopted JST 73FXZ-RSM1-G-ETF(LF)(SN) connectors mentioned in section 3.2.5).

### 3.3.2 The Multi-Purpose Digitizer modules

The JLab DAQ group adopted the VME standard with VXS extension. Therefore, a compliant MPD module, shown in Figure 3.11, has been designed which has the possibility to handle up to sixteen front-end cards. It
has indeed sixteen 12-bit ADCs (ADS5270) running at 40 MHz which each digitize the serial analog output of one front-end card. Apart from that, a MDP module hosts the signals transmitter and receiver to/from the front-end cards, the control logic, the pedestal\(^3\) compensation and the zero suppression logic. The core of the board is an Altera ARRIA GX FPGA [68]. A large memory buffer (128MB DDR DRAM) is present and, in addition to the main VME interface, other communication facilities are included such as [69]:

- a high speed optical link (up to 4 Gb/s),
- a 10-100 Ethernet port,
- a low speed USB 1.1 port.

### 3.4 High voltage system

Seven high voltages (HV) are needed inside a triple-GEM detector, as already shown on the principle schematics in Figure 2.15. However, in the case of our GEM chambers, the (present) plan is to generate these seven voltages independently, instead of using a resistor network to produce them from one single HV channel, as applied in the COMPASS experiment. The drawback of such a resistor network is that the combination of voltages is determined by the values of the used resistors, whereas with seven independent channels the flexibility is higher but a particular attention has to be paid when switching the chamber on and off (a suitable ramp setting is needed in order to prevent irreversible damage to the GEM foils). Our seven independent voltages will be floating, just like the read-out planes, for which the reference will be provided on each strip by the APV25 chip, through an input protection circuit made up of two diodes in inverse polarity between the strip and the ground and power levels (cf. Figure 3.12). The HV distribution of a GEM chamber will be segmented in order to reduce the severity of electrical discharges based on the principles outlined in section 2.3.

\(^3\)The baseline values of the individual channels are called pedestals.
Figure 3.11: The Multi-Purpose Digitizer module [67].

Figure 3.12: Principle of the input protection circuit of the APV25 chip.
3.5 Proportional mode

GEM trackers are gas detectors operated in the proportional mode. Therefore, they could be used for particle identification based on the energy deposited by the particle in the detector, but this will not be the case for the SBS GEM chambers. Their proportional mode will however provide useful information for the suppression of background and ghost hits. Background hits, which are not correlated with the trigger, will produce analog signals with a random evolution over time, instead of showing a sort of long-tailed gaussian-like shape. Ghost hits are artefacts bound to the structure in strips of the read-out plane. If for example two events are detected at the same time, a signal on two X-strips and two Y-strips can be found, leading to 4 intersection points from which only two correspond to physical hits (the other two are called ghost hits). The amplitude correlation of the signals along the X and Y directions will be used to distinguish between physical and ghost hits; only hits with an amplitude correlation within a predefined confidence level shall be accepted.
Chapter 4

Development activities

4.1 Study and optimization of the gas system

4.1.1 Overview and motivation

The COMSOL Multiphysics software has been used to perform a computational fluid dynamics study of the continuous gas flow in the 2 mm gap in between two GEM foils of a single 40 x 50 cm\(^2\) module of the GEM tracker. The permanent gas flow in a module is required to provide the expected gain and signal timing, to evacuate gas that contaminates the mixture and to prevent fast aging of the detector due to radiation-induced chemical reactions in the gas. The gas flow should be spatially uniform in order to guarantee a homogeneous and stable detector response. Therefore, the goal of our study was to optimize the design of the frame separating two GEM foils in order to obtain a better gas flow uniformity over the active area of the module. In the following sections, we give a short introduction to the COMSOL Multiphysics package, to the Finite Element Method and to the fluid dynamics model on which our simulations rely. Then, in section 4.1.5, the optimization of the frame design is summarized through the results of six simulations, involving progressive modifications in the simulated geometry. The overall gas flow uniformity has been compared for the several designs, first qualitatively and then also quantitatively. Finally, since the same simulations provide also the pressure distribution, a short analysis of the computed pressure losses inside the frame is given as well.
4.1.2 The COMSOL Multiphysics package

COMSOL Multiphysics [70] is a software useful for modeling and solving all kinds of scientific and engineering problems based on Partial Differential Equations (PDE). These PDE can be inserted in coefficient form, in general form or in weak form using the corresponding PDE mode of COMSOL. Rather than describing the problem by defining its underlying equations, the user can also work with one of the many built-in physics modes, in which the equations are already defined and only the relevant physical quantities should be inserted by the user (such as material properties, fluxes, loads, etc.). Various types of analyses can be performed with the built-in physical models, including stationary and time-dependent analyses, linear and nonlinear analysis, and eigenfrequency and modal analyses. COMSOL Multiphysics then internally compiles a set of PDE representing the entire model. To solve them, it runs a Finite Element Method (FEM) analysis together with adaptative meshing and error control using a variety of numerical solvers [70].

The Finite Element Method approximates a PDE problem with a discretization of the original problem based on a mesh, which is a partition of the geometry into small units of simple shape called mesh elements. Instead of searching the exact solution to the PDE problem, the method looks for a solution in the form of a piecewise polynomial function, each mesh element defining the domain for one “piece” of it (which has to be a polynomial function) [71]. Such a piecewise polynomial function will be expressed as a linear combination of a finite set of predefined basis functions. The coefficients of the linear combinations are unknown and are called the degrees of freedom [72]. Most of the COMSOL physics interfaces insert these linear combinations in the weak form of the PDE in order to generate a system of equations that is then solved for the degrees of freedom [70].

Let us consider for example a 2-dimensional problem with a single dependent variable \( p(x, y) \). We would like to solve this problem based on a mesh with quadratic triangular elements. The expression “quadratic elements” refers to the fact that on each mesh element the sought piecewise polynomial function \( p^*(x, y) \) is at most a quadratic polynomial. In this case, the solution is expressed as:

\[
p(x, y) \approx p^*(x, y) = \sum_{i=1}^{n} p_i \phi_i(x, y),
\]  

(4.1)
where $i$ refers to a node of the mesh, $p_i$ are the degrees of freedom, $\phi_i(x, y)$ are the basis functions and $n$ is the total number of nodes, under the assumption that each triangle of the mesh possesses six nodes: three corner nodes and three mid-side nodes [71]. A basis function $\phi_i(x, y)$ has here the restriction to be a polynomial of degree at most 2 such that its value is 1 at node $i$ and 0 at all other nodes [70]. The degree of freedom $p_i$ is thus the value of $p^*(x, y)$ at node $i$. The definition of the basis function associated to each node of the mesh can be derived using for example a general method introduced by Silvester in 1969 [72].

### 4.1.3 COMSOL’s Thin-Film Flow Model

All of COMSOL’s single-phase fluid flow interfaces are based on the three fluid dynamics conservation equations known as the Navier-Stokes equations [70]:

- the conservation of mass:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0, \tag{4.2}
\]

- the conservation of momentum:

\[
\rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \cdot \nabla) \vec{u} = -\nabla p + \nabla \cdot \tau + \vec{f}, \tag{4.3}
\]

- the conservation of energy (formulated here in terms of temperature):

\[
\rho C_p \left( \frac{\partial T}{\partial t} + (\vec{u} \cdot \nabla) T \right) = -\nabla \cdot \vec{q} + \tau : S - \frac{T}{\rho} \frac{\partial \rho}{\partial T} \left( \frac{\partial p}{\partial T} + (\vec{u} \cdot \nabla) p \right) + \vec{Q}, \tag{4.4}
\]

where $\rho$ is the density, $t$ is the time, $\vec{u}$ is the velocity, $p$ is the pressure, $\tau$ is the viscous stress tensor, $\vec{f}$ is the volume force vector, $C_p$ is the specific heat capacity at constant pressure, $T$ is the temperature, $\vec{q}$ is the heat flux vector, $S$ is the strain rate tensor and $\vec{Q}$ represents the heat sources.

The operation “:” denotes the contraction between two tensors defined by:

\[
\tau : S = \sum_i \sum_j \tau_{ij} S_{ij}, \tag{4.5}
\]

and the strain rate tensor $S$ is given by:

\[
S = \frac{1}{2} \left( \nabla \vec{u} + (\nabla \vec{u})^T \right). \tag{4.6}
\]
In the case of gases, the equation system can be closed with, for example, the expression of the viscous stress tensor of a Newtonian fluid:

\[
\tau = 2\mu S - \frac{2}{3}\mu (\nabla \cdot \vec{u}) I,
\]

where \(\mu\) is the dynamic viscosity given in [Pa\cdot s] and \(I\) is an identity matrix.

The model that has been used in our simulations is called the Thin-Film Flow Model [73] and belongs to the Computational Fluid Dynamics (CFD) module, which is an add-on package for COMSOL Multiphysics. The Thin-Film Flow Model can be used to model a thin channel of fluid located between two moving structures, as schematized on Figure 4.1. The upper structure is referred to as the moving structure and the lower one as the channel base. Initially, both structures are surrounded by gas with a constant pressure \(p_a\) and the fluid can freely move into and out of the gap. Due to the movements of the structures, an additional and usually time-dependent pressure \(p_f\) appears in the gas inside the gap, which produces a normal force \(F_n\) on the structures. Also a viscous drag force \(F_t\) is created which resists the tangential movement of the structure.

In the Thin-Film Flow Model, it is however assumed that:

- The film thickness \(h\) remains always very small with respect to the dimensions of the solid structures.
- The channel curvature is small.

Therefore, also the following assumptions are made:
• The inertial effects in the fluid are negligible compared to the viscous
effects, thus the flow is laminar.
• The pressure \( p = p_a + p_f \) is constant over the film thickness \( h \).
• The velocity profile over the film thickness is parabolic.
• The fluid is isothermal.

Given these assumptions, solving the fluid flow problem with the Navier-
Stokes equations reduces to solving the following equation, called the Reynolds
equation [73]:

\[
\frac{\partial (\rho h)}{\partial t} + \nabla_{tg} \cdot (\rho h \vec{U}) - \rho (\nabla_{tg} \Delta h_m \cdot \vec{u}_m - \nabla_{tg} \Delta h_b \cdot \vec{u}_b) = 0,
\]

(4.8)

where \( \rho \) is the density, \( h = h_0 + \Delta h_m + \Delta h_b \) is the film thickness, \( t \) is the time,
\( \nabla_{tg} \) is a gradient computed only with the tangential derivatives along the
channel boundaries, \( \vec{U} \) is the mean film velocity, \( \Delta h_m \) and \( u_m \) are respectively
the normal displacement and the tangential velocity of the so-called “moving
structure”, \( \Delta h_b \) and \( u_b \) are respectively the normal displacement and the
tangential velocity of the so-called “channel base”.

The mean film velocity \( \vec{U} \) is actually a function of the pressure \( p \), the dynamic
viscosity \( \mu \), the film thickness \( h \), the tangential velocities \( u_m \) and \( u_b \) of the
solid structures and the relative flow rate function \( Q_{ch} \) that accounts for
possible rarefied gas effects (for cases in which the continuum assumption is
no longer valid, like for example in microsystems):

\[
\vec{U} = -\frac{\nabla_{tg}P_{ch}h^2}{12\mu} + \frac{u_m + u_b}{2}.
\]

(4.9)

One uses \( Q_{ch} = 1 \) when the continuum assumption is valid, i.e. when the
Knudsen number given by \( Kn = \frac{\lambda}{h} \), where \( \lambda \) is the mean free path of the gas
molecules and \( h \) the film thickness, is negligible compared with 0.1. Other-
wise, the Thin-Film Flow Model should be used with a slip model that leads
to a specific function for \( Q_{ch} \) (see reference [73]).

From the equations (4.8) and (4.9), we can see that the Thin-Film Flow
Model has only a single dependent variable, which is the pressure, or more
exactly, the film-variation pressure \( p_f \), since \( p = p_a + p_f \) where \( p_a \) is a constant.

By default, the discretization for this physical model involves quadratic ele-
ments.
4.1.4 Adopted approach

In our simulations, we have used the Thin-Film Flow Model (cf. section 4.1.3) to study the flow of an Ar-CO$_2$ (70/30) gas mixture between two 2 GEM foils inside a single 40 x 50 cm$^2$ module. In this way, we have thus neglected the holes in the GEM foils.

The geometry of the frame separating two GEM foils has been constructed in 2 dimensions, whereas the third dimension, which corresponds to the gas film thickness, has been inserted as a parameter of the physical model. Actually, two separate Thin-Film Flow models, have been defined in order to account for the two different film thicknesses in the problem: 2 mm in between two GEM foils and 1 mm inside the openings of the frame’s spacers and inside the inlets and the outlets.

As far as the inlets and outlets are concerned, it has not been possible to define their exact configuration, because this requires to use a physical model that can be applied to a geometry constructed in 3 dimensions. The Thin-Film Flow model, however, can only be applied to a 2-dimensional geometry. Therefore, we have defined inlets and outlets as 8 mm x 5 mm rectangular zones with a uniform film thickness of 1 mm. Our choice of working with a 2-dimensional geometry is actually bound to the available computational capacity. A simulation with a sufficiently refined 3-dimensional model of the full frame requires indeed a much greater capacity.

Thus, it should be taken into account that our simulations probably do not give a realistic idea of the velocity field inside and nearby the inlets and outlets. Another remark is that also inside and nearby the openings of the spacers, the computed values could be less accurate than inside the 2 mm thick sectors, because the Thin-Film Flow Model is based on the hypothesis that the dimensions of the solid structures should be much larger than the film thickness, which is not the case for the spacers, whose width (0.30 mm) is actually lower than the local film thickness (1 mm).

Typical flows in gas detectors correspond to 1 to 3 volume renewals per hour. If the 3 GEM modules of one chamber are connected to each other in series with respect to the gas flow, the total gas volume for a 2 mm thick “floor” of the chamber is approximately $3 \cdot 0.4 \cdot 0.5 \cdot 0.002 = 0.0012$ m$^3$, so 1 to 3 volume renewals per hour correspond in our case to gas flows between 20 cm$^3$/min and 60 cm$^3$/min. Nearly all our simulations have therefore been made with a total flow of 60 cm$^3$/min imposed at the inlets. Later on,
two simulations have also been rerun with a ten times higher flow (see the quantitative analysis in section 4.1.5), because higher volume renewal rates might be used in order to reduce the aging effects (consider for example reference [74], in which aging tests with flows on the order of 1 volume renewal per minute are reported).

In a frame with 2 inlets, having each a cross-section of 8 mm$^2$, the mean entrance velocity is then $U_e = 0.0625$ m/s. If one wants to evaluate whether such a stationary gas flow is incompressible or not, the mean velocity should be compared to the speed of sound in the same medium [70]. For an ideal gas, the speed of sound is given by the following formula:

$$U_s = \sqrt{\frac{\gamma RT}{M}}, \quad (4.10)$$

where $\gamma$ is the adiabatic constant of the gas (worth $5/3$ for single atoms, $7/5$ for diatomic molecules and $4/3$ for molecules made up of more than 2 atoms), $R = 8.314$ J/(mol·K) is the universal gas constant, $T$ is the temperature and $M$ is the molecular mass of the gas. In our case, we consider that $\gamma \approx 5/3$ since argon is the main component of the gas mixture; the temperature $T$ is constant and equal to 293.15 K and $M \approx 0.70 \cdot 0.03995 + 0.30 \cdot 0.04401 = 0.04117$ kg/mol. For the speed of sound, we thus obtain $U_s \approx 314$ m/s $>>> U_e = 0.0625$ m/s. Therefore, it has been assumed that the gas flow is incompressible and a constant value has been used for the density $\rho$. Also for the dynamic viscosity $\mu$, a constant value has been used since the variation of $\mu$ over the considered pressure ranges can reasonably be assumed negligible. Somehow, it is useful to get rid of the pressure dependence of the density and the dynamic viscosity, because the more scope there is for variation in the terms of the equations to be solved, the harder it is for the numerical solvers to reach convergence.

In the two defined Thin-Film Flow Models, instead of considering two moving solid structures, we have forced the normal displacements, $\Delta h_m$ and $\Delta h_b$, and the tangential velocities, $u_m$ and $u_b$, of these structures to zero, so that the film thickness $h$ would remain constant to its initial value $h_0$. We have also assumed in the first place that the fluid can be treated as a continuum. Actually, the Knudsen number obtained with our no-slip models was around $5 \cdot 10^{-5}$, which is indeed negligible with respect to 0.1. Moreover, we have made the assumptions that the density $\rho$ and the dynamic viscosity $\mu$ are constant in this problem.
With all of these assumptions, the expression (4.9) of the mean film velocity reduces to:

\[
\vec{U} = -\frac{h^2}{12\mu} \vec{\nabla}_{tg} p, \quad (4.11)
\]

and the Reynolds equation (4.8) simplifies into:

\[
\vec{\nabla}_{tg} \cdot \vec{U} = 0 \quad \Leftrightarrow \quad \vec{\nabla}_{tg} \cdot \vec{\nabla}_{tg} P = 0 \quad \Leftrightarrow \quad \vec{\nabla}_{tg} \cdot \vec{\nabla}_{tg} p_f = 0. \quad (4.12)
\]

As boundary conditions:

- We have imposed a uniform perpendicular velocity (e.g. 0.0625 m/s) on the external 8 mm side of the inlets.
- On the external 8 mm side of the outlets, we have forced the additional pressure \( p_f \) to zero.
- “Walls” have been inserted on the sectors of the geometry that represent surfaces of the frame. This imposes the standard wall boundary condition \( \vec{U} = \vec{0} \) on these sectors.

The ambient pressure \( p_a \) has been set to 1 atm. However, the solution for the velocity field does not depend on this value. The obtained velocity field does not depend either on the value of the constant density \( \rho \) which, for a Ar-CO\(_2\) (70/30) mixture at 20°C and 1 atm, can be computed using the densities at 20°C and 1 atm of respectively argon and carbon dioxide (\( \rho_{Ar} = 1.7837 \text{ kg/m}^3 \) and \( \rho_{CO_2} = 1.9770 \text{ kg/m}^3 \)), with the following formula:

\[
\rho = 0.70 \cdot \rho_{Ar} + 0.30 \cdot \rho_{CO_2} = 1.8417 \text{ kg/m}^3. \quad (4.13)
\]

The computed velocity field depends nevertheless on the value of the dynamic viscosity \( \mu \). To compute the dynamic viscosity at 20°C and 1 atm of the Ar-CO\(_2\) (70/30) mixture, we have used Reichenberg’s formula \([75]\) with the parameters listed in Table 4.1. The details of the calculation are given in Appendix B. We have obtained:

\[
\mu = 1.9696 \cdot 10^{-5} \text{ Pa} \cdot \text{s}. \quad (4.14)
\]

When simulating a system that is quite complex, it is advised to start with a strongly simplified geometry (treat for example the geometry in parts) and increase progressively the complexity of the model, as one’s knowledge of the
CHAPTER 4. DEVELOPMENT ACTIVITIES

<table>
<thead>
<tr>
<th>Property</th>
<th>Ar</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume fraction</td>
<td>0.70</td>
<td>0.30</td>
</tr>
<tr>
<td>Dynamic viscosity [µPoise]</td>
<td>225.60</td>
<td>144.90</td>
</tr>
<tr>
<td>Molecular mass [g/mol]</td>
<td>39.9480</td>
<td>44.0100</td>
</tr>
<tr>
<td>Dipolar momentum [Debye]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Compressibility factor</td>
<td>0.9993</td>
<td>0.9942</td>
</tr>
<tr>
<td>Critical temperature [K]</td>
<td>150.86</td>
<td>304.12</td>
</tr>
<tr>
<td>Critical pressure [bar]</td>
<td>48.98</td>
<td>73.74</td>
</tr>
</tbody>
</table>

Table 4.1: Values of the parameters used to compute the dynamic viscosity of the Ar-CO₂ (70/30) mixture at 20°C and 1 atm.

Simulation increases [70]. Therefore, we have started by simulating a frame with only two sectors, separated by a spacer containing just one opening of length 15 mm. One inlet (with velocity 0.0625 m/s) and one outlet have been defined. The problem has been treated as stationary and a predefined mesh type of COMSOL (called “Normal”) has been used, which in our case is made up of 24182 unstructured quadratic triangular elements (cf. the example in 4.1.2). The obtained velocity field is shown in Figure 4.2.

In a next step, we have simulated six adjacent sectors of the frame and included two 15 mm openings in each spacer. To reach convergence for this problem, it has been useful defining a time-dependent model in which the inlet velocity increases smoothly from 0 to 0.0625 m/s. We are however not interested in this evolution in the first place and we focus on the results obtained for the final state (cf. Figure 4.3). In this simulation, we have also tried out a more complex mesh, consisting of a predefined “Fine” unstructured quadratic triangular mesh in the central regions (133276 elements) and a “Boundary Layer”, made up of parallel rectangular quadratic elements along the borders of the geometry (39252 elements). Notice that on Figure 4.3, the scale has been cut at a tenth of the maximum velocity.

Hereafter, we have made the gas flow simulation for the full frame in its first prototype version (cf. Appendix A). Based on these results, which are discussed in the next section, we have tried to modify some aspects of the frame’s design in order to reduce, in number and/or in size, the zones with particularly high or low velocities. The optimization of the frame design has been realized by gradually modifying the simulated geometry and comparing
Figure 4.2: Velocity magnitude on a linear scale and streamlines of the velocity field obtained in the case of a frame with 2 sectors, 1 inlet (left) and 1 outlet (right). The two sectors communicate through a central opening of 15mm.
Figure 4.3: Velocity magnitude on a linear scale and streamlines of the velocity field obtained in the case of a frame with 6 sectors, 1 inlet (left) and 1 outlet (right). Two adjacent sectors communicate through two openings of 15mm.
each time the new results with those from previous simulations.

In all our simulations of full-sized frame versions, we have used the time-dependent model but without working with the same type of mesh as in the six-sectors simulation, because of the too large number of elements (over 500000). Hence, we have defined another type of customized mesh consisting of three predefined unstructured quadratic triangular mesh types:

- in the inlets and outlets, as well as in a 16 x 10 mm$^2$ rectangular zone in front of each of them, we have defined a “Finer” (resp. “Extremely fine”) mesh, in the first two simulations (resp. the last four ones).
- in a 15 mm (resp. 20 mm) thick zone along all the other boundaries, we have defined a “Fine” (resp. “Extra fine”) mesh, in the first two simulations (resp. the last four ones).
- in the rectangles left over in the center of the several frame sectors, we have defined a “Normal” (resp. “Finer”) mesh, in the first two simulations (resp. the last four ones).

In this way, we have tried to refine our meshes without exceeding 250000 elements. Since the geometry is different in every simulation, even when we try to design the meshes in similar ways, all of them are different. In order to assess in some way the precision of our various simulations, we have compared for each simulation the inlet and the outlet total fluxes based on the computed velocity field (cf. section 4.1.5). Since the flow is supposed to be conserved, these fluxes should in theory be equal and, of course, correspond to the initially imposed value (e.g. 60 cm$^3$/min).

### 4.1.5 Analysis and results

#### Simulation 1: Full frame in its first prototype version

In its first prototype version, the frame separating two GEM foils possesses 18 sectors, 2 inlets and 2 outlets. Two adjacent sectors along the longest side of the module communicate through 2 openings of 15 mm, while two adjacent sectors along the other direction communicate through a single 15 mm opening. In our simulation, the uniform velocity imposed on both inlets is 0.0625 m/s, which corresponds to a total flow of 60 cm$^3$/min. Figure 4.4 shows the velocity magnitude on a linear scale, together with the streamlines
of the velocity field that has been obtained. Notice that the scale has been cut at a tenth of the maximum velocity. A contour plot with logarithmic scale of the velocity magnitude is also given in Figure 4.5.

As expected, the zones with lower velocities are found mainly in corners where spacers cross each other or reach the border of the frame, and in the four corners of the outer structure of the frame. However, our attention has also been drawn towards two large low flux zones at the extremities of the central 6-sectors row, which does not contain inlets and outlets. For this reason, in our next simulation we have included an extra inlet and outlet, placed at the level of this central row.

Zones with higher velocities correspond to inlets, outlets and openings in the spacers, especially in the spacers parallel to the shortest side of the module. Figure 4.6 shows a close-up on one of the inlets. The full linear scale has been selected on this picture. Although our simulation is not the most appropriate to estimate the actual velocity field in the region of inlets and outlets (cf. section 4.1.4), we can realize from it that the 90 degrees angles between an inlet (or outlet) and the borders of sectors are responsible for particularly high velocities, which are in fact also much higher than in the openings of spacers (cf. Figure 4.7). The maximum velocity computed by the simulation (0.0689 m/s) is indeed found on these edges at the inlets and outlets. Thereupon, we have decided also to replace in our next simulation these 90 degrees edges by circular joints of radius 1.5 mm.
Figure 4.4: Simulation 1 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained in the case of the full frame in its first prototype version. The two inlets (resp. outlets) are on the left (resp. right) side of the figure.
Figure 4.5: Simulation 1 – Contour plot with logarithmic scale of the velocity magnitude obtained in the case of the full frame in its first prototype version. The two inlets (resp. outlets) are on the left (resp. right) side of the figure.
Figure 4.6: Simulation 1 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for one of the two inlets in the first prototype version.

Figure 4.7: Simulation 1 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for an opening in a spacer of the full frame in its first prototype version.
Simulation 2: Modifications to the inlet and outlet configuration

In this second simulation, one inlet and one outlet have been added with the aim to improve the uniformity of the gas flow in the central 6-sectors row of the frame. The exact positions of these inlet and outlet have been selected based on the available space in the detector. For all inlets and outlets, the aforementioned circular joints of radius 1.5 mm have also been introduced. The 60 cm$^3$/min flow has been maintained, resulting in an inlet velocity of 0.04167 m/s. In Figure 4.8, the obtained velocity magnitude is shown on a linear scale (cut to a tenth of the maximum velocity), together with the streamlines. Figure 4.9 is a contour plot of the velocity magnitude with a logarithmic scale. On a qualitative basis, the overall uniformity of the velocity magnitudes looks improved by the added inlet and outlet. It seems that in this configuration we obtain in the six-sectors rows three relatively independent and similar flows. In order to show the effect of the circular joints at inlets and outlets (cf. Figure 4.11), we have also run the same simulation using the initial geometry of the inlets and outlets (cf. 4.10). Figures 4.10 and 4.11 share the same color scale, so that the slight reduction of the high velocities inside the sector is visible for the design with circular joints. Getting rid of these 90 degrees edges is anyhow a way to stabilize the boundary layers. It will help avoiding their separation from the walls and thus avoiding possible small turbulence areas near the inlets and outlets.

Simulation 3: Reduction of the number of sectors from 18 to 12

Since low velocity zones are found where spacers cross each other or reach the border of the frame, reducing for example the number of spacers would be a way to reduce these “stagnation” zones in number, which might thus improve the overall uniformity of the gas flow. The spacers should however continue to insure the planarity of the GEM foils.

A sector of a GEM foil glued to its frame can be modelled as a built-in rectangular thin plate of area $S$, being isotropically stretched by a uniform force per unit length $T$ at its circumference, and undergoing a normal pressure $P$. The maximum deformation $u_{\text{max}}$ of such a plate is given by the following expression [76]:

$$u_{\text{max}} = \kappa(\zeta) \frac{PS}{T},$$

(4.15)
Figure 4.8: Simulation 2 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for an 18-sectors frame with 3 inlets (left) and 3 outlets (right).
Figure 4.9: Simulation 2 – Contour plot with logarithmic scale of the velocity magnitude obtained for an 18-sectors frame with 3 inlets (left) and 3 outlets (right).
where the geometrical factor $\kappa(\zeta)$ is an increasing function of the ratio $\zeta \in [0, 1]$ of the rectangle sides. For a square plate, $\kappa$ reaches a maximum value of nearly 0.074 [76].

In our case, we want the maximum deformation $u_{\text{max}}$ to remain lower than 1% of the 2 mm thick gap between two GEM foils, at a pressure $P$ up to 10 N/m$^2$, when a tension of 1 kg/cm ($T = 9.81$ N/cm) is applied to the GEM foil. If we consider in first approximation a geometrical factor $\kappa$ of 0.074, the maximum allowable area $S$ of a sector should thus be:

$$S = \frac{u_{\text{max}} T}{\kappa P} = \frac{2 \cdot 10^{-5} \cdot 9.81 \cdot 10^2}{0.074 \cdot 10} = 2.65 \cdot 10^{-2} \text{ m}^2.$$ (4.16)

Based on these assumptions, it would have been feasible to reduce the number of sectors to only 9 (using 2 spacers along both directions), since the area of each sector would have been equal to $\frac{0.2 \text{ m}^2}{9} = 2.22 \cdot 10^{-2} \text{ m}^2$. However, a more conservative choice of 12 sectors (2 spacers along the long side and 3 spacers along the short one) has been made, which results in sectors of about $0.125 \times 0.133 \text{ m}^2 = 1.66 \cdot 10^{-2} \text{ m}^2$. When looking at the Figures 4.12 and 4.13, showing the simulation results for a frame with 12 sectors, the overall uniformity of the gas flow seems indeed improved by the reduction of the number of spacers along the shortest side of the module.
Figure 4.12: Simulation 3 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for a 12-sectors frame with 3 inlets (left) and 3 outlets (right).
Figure 4.13: Simulation 3 – Contour plot with logarithmic scale of the velocity magnitude obtained for a 12-sectors frame with 3 inlets (left) and 3 outlets (right).
Simulation 4: Enlargement of some openings in the spacers

With the hope to further improve the flow uniformity, especially in the sectors possessing an inlet or an outlet, we have made a simulation in which the openings in the spacers that delimit these particular sectors are enlarged from 15 to 20 mm. The results have however not been so convincing. The Figures 4.14 and 4.15 do not show a net improvement of the flow uniformity when compared for example to Figures 4.12 and 4.13 of Simulation 3. Only small differences can be noticed nearby the enlarged openings of the short spacers, where the velocities have been a little bit decreased, but this is not a meaningful improvement in our opinion. For this reason, the idea of modifying the width of the openings in spacers has been abandoned.

Simulation 5: Nine openings in the spacers along the short side of the module

Good results have been obtained with nine openings of 10 mm instead of six openings of 15 mm for the spacers along the short side of the module. When comparing Figure 4.16, and especially Figure 4.17, with the figures from previous simulations, we notice a reduction in size of the low velocity zones where spacers cross each other and where the short spacers reach the longest border of the frame.

Simulation 6: Doubling the openings in the spacers along the long side of the module

Based on the results of Simulation 5, we have also tried to find out whether doubling the number of 15 mm openings in the spacers along the longest side would decrease the size of the large low velocity zones near the shortest borders of the frame. However, these long spacers are parallel to the main direction of the gas flow, instead of being perpendicular to it like the short spacers. For this reason, increasing the number of openings in the long spacers does not produce the same positive effect on the flow uniformity, as one can see from Figures 4.18 and 4.19. We have decided in consequence to stick with the frame design of Simulation 5, since in Simulation 6 we have not found a sufficient improvement of the flow uniformity to justify adding openings in the long spacers and thus weakening the mechanical support they provide. The new frame designs are shown in Appendix A.
Figure 4.14: Simulation 4 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for a 12-sectors frame with 3 inlets (left) and 3 outlets (right), having enlarged openings in the spacers nearby inlets and outlets.
Figure 4.15: Simulation 4 – Contour plot with logarithmic scale of the velocity magnitude obtained for a 12-sectors frame with 3 inlets (left) and 3 outlets (right), having enlarged openings in the spacers nearby inlets and outlets.
Figure 4.16: Simulation 5 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for a 12-sectors frame with 3 inlets (left) and 3 outlets (right), having nine 10 mm openings in the spacers along the short side of the module.
Figure 4.17: Simulation 5 – Contour plot with logarithmic scale of the velocity magnitude obtained for a 12-sectors frame with 3 inlets (left) and 3 outlets (right), having nine 10 mm openings in the spacers along the short side of the module.
Figure 4.18: Simulation 6 – Velocity magnitude on a linear scale and streamlines of the velocity field obtained for a 12-sectors frame with 3 inlets (left) and 3 outlets (right), having nine 10 mm openings in the short spacers and eight 15 mm openings in the long spacers.
Figure 4.19: Simulation 6 – Contour plot with logarithmic scale of the velocity magnitude obtained for a 12-sectors frame with 3 inlets (left) and 3 outlets (right), having nine 10 mm openings in the short spacers and eight 15 mm openings in the long spacers.
### CHAPTER 4. DEVELOPMENT ACTIVITIES

#### Table 4.2: Comparison of the total inlet and outlet fluxes obtained in the six simulations.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Sectors</th>
<th>Mesh elements</th>
<th>Imposed flux [m$^3$/s]</th>
<th>Obtained inlet flux [m$^3$/s]</th>
<th>Obtained outlet flux [m$^3$/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2</td>
<td>24182</td>
<td>5.0000E-07</td>
<td>5.0003E-07</td>
<td>5.0002E-07</td>
</tr>
<tr>
<td>b</td>
<td>6</td>
<td>172528</td>
<td>5.0000E-07</td>
<td>5.0000E-07</td>
<td>5.0000E-07</td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>116229</td>
<td>1.0000E-06</td>
<td>1.0001E-06</td>
<td>9.9991E-07</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>216826</td>
<td>1.0000E-06</td>
<td>9.9992E-07</td>
<td>9.9997E-07</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>163507</td>
<td>1.0000E-06</td>
<td>9.9990E-07</td>
<td>9.9989E-07</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>172051</td>
<td>1.0000E-06</td>
<td>9.9990E-07</td>
<td>9.9989E-07</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>170085</td>
<td>1.0000E-06</td>
<td>9.9990E-07</td>
<td>9.9989E-07</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>178997</td>
<td>1.0000E-06</td>
<td>9.9990E-07</td>
<td>9.9989E-07</td>
</tr>
</tbody>
</table>

**Comparison of total inlet and outlet fluxes**

In Table 4.2, we have compared for all previously mentioned simulations, the imposed total flux at the inlets with the computed total inlet and outlet fluxes, as a means to assess the precision of the various calculations. The computed fluxes were obtained by integration of the velocity field over the segments of the geometry corresponding to the external cross-section of the inlets (respectively the outlets), and multiplying this integral by the film thickness $0.001\, m$. The best calculation was obtained with the Boundary Layer mesh used in the simulations with six sectors (cf. 4.1.4). For all simulations of full frames, the absolute relative error of the obtained inlet flux with respect to the imposed flux does not exceed 0.01 %, whereas the difference between the obtained outlet and inlet fluxes is lower than 0.02 % of the computed inlet flux.

**Quantitative comparison of the flow uniformity**

With the aim to compare quantitatively the flow uniformity, we have extracted for each simulation from 1 to 6 the velocity magnitude of 2000 points located on a rectangular grid, which corresponds to about 1 point per cm$^2$. Table 4.3 shows the mean, the minimum and the maximum velocities for these distributions. When comparing the first two simulations, however, one should keep in mind that a third inlet and a third outlet have been added in
Simulation 2, but that the same total flux was set for both. The maximum value in the distribution of Simulation 2 is \( \approx 0.63 \) times the maximum value for Simulation 1, which strongly related to the fact that the imposed inlet velocity is \( \approx 0.67 \) times the inlet velocity in Simulation 1. Probably for the same reason, the minimum and mean velocities are also higher in Simulation 1 than in Simulation 2.

In Table 4.4 and its corresponding graph, Figure 4.20, we have used cumulative frequencies based on fractions of the mean velocity in order to compare the shapes of the several velocity distributions. We consider that a better flow uniformity corresponds to a distribution for which fractions smaller than the mean have smaller cumulative frequencies and fractions larger than the mean, larger cumulative frequencies. We can see the evolution in the flow uniformity from Simulation 1 to Simulation 6, according to what we have qualitatively discussed previously. Simulation 2, with its extra inlet and outlet, shows a significant improvement with respect to Simulation 1, especially for the reduction of the lower velocities in the distribution. Also Simulation 3, in which the number of short spacers has been reduced from 5 to 3, has produced a significant narrowing of the velocity distribution, when compared to Simulations 1 and 2. No real improvement is indeed observed for the larger spacer openings in Simulation 4, while Simulation 5 with its nine openings in the short spacers corresponds very clear to a more uniform distribution. The results of simulation 6 are, as expected, quite equivalent to those of Simulation 5. Globally, this analysis thus confirms our choice of Simulation 5 as the most suitable frame design. According to our 2000-points sampling, in this design about 9% of the points have a velocity lower than one half of the mean velocity (against nearly 20% for the original frame design) and also about 9% of the points have a velocity greater than 1.5 times the mean velocity (against nearly 15% for the original frame). Simulation 1 and 5 have also been run with a 10 times higher total flow (i.e. \( 600 \text{ cm}^3/\text{min} \)) and, as expected from the linearity of the model (cf. equation (4.12)), (almost) the same conclusion has been drawn from the extracted 2000-points data, as deduced from comparing the Tables 4.4 and 4.5. The difference is that for Simulation 1, the found percentage of points with a velocity lower than one half of the mean velocity, lies closer to 19% than to 20%. Figures 4.21 and 4.22 show the results obtained with this 600 cm\(^3\)/min flow for the Simulations 1 and 5 respectively. As expected, the maximum obtained velocities
Chapter 4. Development Activities

Table 4.3: Mean, minimum and maximum velocities of the 2000-points distributions of the six simulations.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Mean velocity [cm/s]</th>
<th>Minimum velocity [cm/s]</th>
<th>Maximum velocity [cm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5494E-01</td>
<td>6.5633E-04</td>
<td>3.0960</td>
</tr>
<tr>
<td>2</td>
<td>1.4380E-01</td>
<td>2.5129E-04</td>
<td>1.9587</td>
</tr>
<tr>
<td>3</td>
<td>1.4021E-01</td>
<td>3.6044E-04</td>
<td>1.9510</td>
</tr>
<tr>
<td>4</td>
<td>1.3997E-01</td>
<td>3.5461E-04</td>
<td>1.9518</td>
</tr>
<tr>
<td>5</td>
<td>1.3811E-01</td>
<td>3.6285E-04</td>
<td>1.9502</td>
</tr>
<tr>
<td>6</td>
<td>1.3811E-01</td>
<td>2.7923E-04</td>
<td>1.9558</td>
</tr>
</tbody>
</table>

are 10 times higher than in the simulations for a 60 cm³/min flow.

Estimate of pressure losses for the final frame

In Figure 4.23, we present a contour plot of the film-pressure variation $p_f$ in the case of the selected frame design (Simulation 5). Using the Thin-Film Flow 2-dimensional model, the computed total pressure loss across the frame is only 0.1642 Pa for a flow of 60 cm³/min. By adjusting the contour lines to the openings in the short spacers, we estimate that the pressure loss due to such a spacer is about 0.0015 Pa, which is very little. Instead, the pressure loss due to the inlets and the outlets is much more important. When comparing the pressure loss across one of the two central sectors (0.0108 Pa) with the one across a sector possessing an inlet (0.0098 Pa), we find that the pressure loss due to the inlet is 0.0590 Pa. In the same way, the pressure loss across the outlets would be 0.0575 Pa. Thus, according to our model the inlets and outlets together are responsible for about 71% of the total pressure loss. However, as we know, our model is certainly not accurate as far as inlets and outlets are concerned, mainly because in the actual frame there is a 90 degrees angle between the flow inside the inlet pipe and the one in the gap in between two GEM foils, which is a transition that we can not simulate with our 2-dimensional model. It would therefore be useful to make a 3-dimensional model of the frame in order to find out with some accuracy how large the pressure loss is across the inlets and outlets, and of course also across the whole module. This information would be of interest for the design of the external gas system. It would for example allow to confirm (or infirm)
Chapter 4. Development Activities

Table 4.4: Percentage of the points that have a velocity lower than a given fraction of the mean velocity, compared for the six simulations.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Fraction of the mean</th>
<th>Cumulative frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0.10</td>
<td>2.50</td>
<td>1.80</td>
</tr>
<tr>
<td>0.25</td>
<td>7.70</td>
<td>4.95</td>
</tr>
<tr>
<td>0.50</td>
<td>19.95</td>
<td>17.05</td>
</tr>
<tr>
<td>0.75</td>
<td>42.90</td>
<td>38.85</td>
</tr>
<tr>
<td>0.90</td>
<td>56.00</td>
<td>50.20</td>
</tr>
<tr>
<td>1.10</td>
<td>73.30</td>
<td>73.40</td>
</tr>
<tr>
<td>1.25</td>
<td>79.15</td>
<td>79.90</td>
</tr>
<tr>
<td>1.50</td>
<td>85.20</td>
<td>87.00</td>
</tr>
<tr>
<td>3.00</td>
<td>97.80</td>
<td>98.40</td>
</tr>
</tbody>
</table>

Table 4.5: Mean, maximum and minimum velocities and percentage of the points that have a velocity lower than a given fraction of the mean velocity, for Simulations 1 and 5 rerun with a 600 cm³/min flow.

<table>
<thead>
<tr>
<th>Simulation (at 600 cm³/min)</th>
<th>1</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean velocity [cm/s]</td>
<td>1.5494</td>
<td>1.3811</td>
</tr>
<tr>
<td>Minimum velocity [cm/s]</td>
<td>6.5633E-03</td>
<td>3.6285E-02</td>
</tr>
<tr>
<td>Maximum velocity [cm/s]</td>
<td>30.960</td>
<td>19.502</td>
</tr>
<tr>
<td>Fraction of the mean</td>
<td>Cumulative frequency (%)</td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>2.50</td>
<td>0.80</td>
</tr>
<tr>
<td>0.25</td>
<td>7.70</td>
<td>2.85</td>
</tr>
<tr>
<td>0.50</td>
<td>19.35</td>
<td>9.10</td>
</tr>
<tr>
<td>0.75</td>
<td>42.80</td>
<td>23.65</td>
</tr>
<tr>
<td>0.90</td>
<td>55.95</td>
<td>48.70</td>
</tr>
<tr>
<td>1.10</td>
<td>73.30</td>
<td>81.30</td>
</tr>
<tr>
<td>1.25</td>
<td>79.15</td>
<td>86.55</td>
</tr>
<tr>
<td>1.50</td>
<td>85.20</td>
<td>91.05</td>
</tr>
<tr>
<td>3.00</td>
<td>97.80</td>
<td>98.55</td>
</tr>
</tbody>
</table>
Figure 4.20: Percentage of the points that have a velocity lower than a given fraction of the mean velocity, compared for the six simulations.
Figure 4.21: Velocity magnitude on a linear scale and streamlines of the velocity field obtained for Simulation 1 rerun for a 600 cm$^3$/min flow.
Figure 4.22: Velocity magnitude on a linear scale and streamlines of the velocity field obtained for Simulation 5 rerun for a 600 cm$^3$/min flow.
whether connecting the gas systems of the three modules of a chamber in series is a better option compared to a parallel connection.
Figure 4.23: Simulation 6 – Contour plot of the film-pressure variation $p_f$. 
4.2 Quality control: high voltage test of GEM foils

4.2.1 Overview of the assembling procedures and needs

Clean room

The assembly of GEM detectors is carried out in a clean room, in which the concentration of airborne particles is kept under specified limits, through air filtration, pressure-, temperature- and humidity control and cleaning procedures [77]. The Department of Physics and Astronomy of the University of Catania possesses a clean room of class 100, meaning that the concentration of airborne particles in this clean room is kept lower than 100 particles (of 0.5 μm or larger) per cubic foot of air [77]. All operators should wear protective clothing, including overshoes, gloves, a hair cover and a face mask.

Global assembling procedure

Our 40 x 50 cm$^2$ triple-GEM modules will be assembled according to a typical procedure (cf. [78], [79] and [80]) with the following main steps:

1. Preparation of the frames: application – outside the clean room – of a polyurethane varnishing spray to avoid spikes, fibers, etc. (curing time of about 24 hours); cleaning in an ultrasonic bath with demineralized water; drying in an oven for several hours.

2. Validation of the frames: high voltage test (the frames should hold 5 kV in air).

3. Validation of GEM foils: optical inspection & high voltage test (cf. section 4.2.2).

4. Validation of the manufactured read-out PCB$^1$: in both direction, the first distance between the first and the last strip should not exceed 0.5 mm from the nominal value.

5. Cleaning of the honeycomb plane (prepared at CERN as shown in Figure 3.5).

6. Gluing of the read-out PCB to the honeycomb plane.

7. Stackering and gluing of the first GEM frame on the readout PCB.

8. Soldering of the 1 MΩ SMD$^2$ limiting resistor on the single-sector side.

---

$^1$Printed Circuit Board

$^2$Surface Mount Device
of the first GEM foil.

9. Stretching and gluing of the first GEM foil of point 8 on its frame (already glued on the readout PCB (see point 7)). Exceeding Kapton is cut to size.

10. A uniform pressure should be applied over the structure during the polymerization of the glue (with loads or with a “vacuum bag” technique [81]).

11. Soldering of the twenty 1 MΩ SMD resistors on the sectorized side of the first GEM foil.

12. The stack is removed from the stretcher. The high voltage test is performed on the GEM foil that has just been glued to the stack.

13. The steps 7 to 12 are repeated for the other 2 GEM frames and foils (replace “read-out PCB” with “previous GEM foil”).

14. Stackering and gluing of the drift frame to the stack.

15. Gluing of the drift foil to the stack.

16. Stackering and gluing of the entrance frame to the stack.

17. Gluing of the entrance mylar foil to the stack.

18. Stackering and gluing of the cover frame to the stack.

19. Sealing of the module with an insulating agent (e.g. Dow Corning, which has a polymerization time of about 6 hours at room temperature).

The used epoxy glue is prepared by mixing an epoxide resin and its polyamine hardener (e.g. resin Araldit AY103 + hardener HD991) and can be used for about 1 hour. The polymerization takes around one day at room temperature and mainly for this reason the whole assembling procedure of a module takes about two weeks.

**GEM stretcher**

The stretching of the GEM foils is performed with a device specifically designed for this, that we shall call a “GEM stretcher”. Figure 4.24 shows a GEM foil which is being stretched by such a device while its frame is being glued to it. The foil is clamped with jaws and the applied tension to its circumference (e.g. 2 kg/cm) is monitored with load cells, which are S-shaped strain gauge meters. Note that the Kapton creep is negligible for the applied tension. Figure 4.25 is a drawing of the GEM stretcher that has been used to produce our first 40 x 50 cm² prototype module.
CHAPTER 4. DEVELOPMENT ACTIVITIES

Figure 4.24: Picture of a frame being glued to a stretched GEM foil [43].

Figure 4.25: Drawing of the GEM stretcher that has been used to build the first $40 \times 50 \text{ cm}^2$ prototype module [82].
4.2.2 Quality control procedures for GEM foils

After the manufacturing, a first quality check of the GEM foils is performed at CERN. If the resistivity in air between the two sides exceeds 2 GΩ per sector and the hole diameter and pitch are $70 \pm 5 \, \mu\text{m}$ and $140 \pm 5 \, \mu\text{m}$ respectively, the GEM foils can be delivered [78]. Only GEM foils which thereupon pass the optical inspection and the high voltage test, can be used to build a GEM module. Quality checks of GEM foils are important, because impurities (dust), scratches and etching defects, such as missing holes, enlarged holes, joint holes, missing copper, overhanging copper and cracks in the Kapton, will affect the amplification properties of a foil.

Optical inspection

First, a manual optical inspection of the GEM foil is done by eye in order to assess its global state (mainly the cleanness and the presence of scratches). Then, the GEM foil undergoes the high voltage test (see further). If the GEM foil does not show the desired behaviour during the high voltage test, a more extensive optical inspection of the anomalous sector(s) is performed manually under the microscope in order to localize the cause of the problem. Note that one of the quality criteria is that holes should not be cut at sector separations [78].

High voltage test

For the high voltage test, the GEM foil (or later on, the assembly under construction) should be placed inside a clean Plexiglas box that is flushed with dry nitrogen gas (minimum flow 15 l/h [78]), in order to reduce the moisture level and provide a stable and reproducible environment. Even before applying voltage, flushing the closed box during 2 or 3 hours is necessary to evacuate air and contaminating impurities. The aim of the high voltage test is to check the leakage current through the insulating Kapton layer of the GEM foil when a voltage, up to about two times the nominal operating voltage, is applied on the two external copper layers. An anomalous behaviour during the test can indicate the presence of problematic manufacturing defects in the foil, so in this respect the high voltage test plays a crucial role in the quality control of GEM foils.
During the test, the voltage should be increased progressively, in “steps”, because strong discharges that could damage the foil should be avoided. The test can be performed sector by sector or on the whole GEM foil. In the latter case, if the protective resistors have not been soldered yet, it is possible to connect, on the sectorized side of the foil, all 20 sector pads together using along each 10-sector border of the foil a copper strip for which the contact with the sector pads is assured by the pressure of pegs (the copper strip is covered with a thicker PVC strip, to distribute the applied forces, and a piece of bakelite to provide support).

In Catania, the high voltage tests of GEM foils will be performed using an electrometer Keithley 6517B, which will both apply the voltage and measure the leakage current. This device has a voltage source that can deliver up to 1000 V and currents can be measured between $1 \cdot 10^{-18}$ A and 20 mA (10 current ranges available). For current measurements, an internal connection should be configured, using the “meter-connect” option, and the required external connections are schematized in Figure 4.26. In Figure 4.27, the procedure that we want to implement for the high voltage test is summarized. This procedure is largely inspired from the references [78] and [79], but we will apply it to the whole GEM foil at once. The voltage has to be increased in steps of 20 V until 660 V. At 100 V, however, it might be useful to maintain the voltage constant for a couple of hours before increasing the voltage further, in order to get rid of impurities sticking to the foil, which can be burnt by the voltage and evacuated by the gas flow. In each step, the current is likely to rise to about 10 nA while the voltage is being increased (typically with a ramp slope of 5 V/s), but our criterion is that, near the end of a step, the current should stabilize under 1 nA. If the criterion is not met, the voltage should be decreased so as to bring the current back under 1 nA. At that point, the voltage can be kept constant for several hours in the hope to cure the foil by the elimination of impurities. Later on, the test procedure can be resumed. If the current rises too much again, the problem might be due to manufacturing defects. The test procedure can then be performed sector by sector in order to identify which sectors are failing. If a voltage of 660 V can be reached while respecting the 1 nA limit, our procedure foresees a stability test: the voltage is increased up to 680 V, just to check whether the current and its fluctuations do not tend to increase, and then the voltage is brought back to 640 V and kept constant for at least one hour. In our
expectations, the current should stay constant around ± 0.5 nA. After that, the test finishes by bringing the voltage back to zero in steps of 100 V.

### 4.2.3 Program development in LabVIEW for the remote control of the high voltage test

A program has been developed in LabVIEW for the remote control of the Keithley 6517B in the high voltage test of GEM foils. The advantages of the remote control are that the voltage ramps are automatically generated, the current measurements are automatically performed, the measured values can be systematically recorded in a text file and the evolution of the test can be followed on a graphic that displays the measured current in real time.

#### Philosophy of the program

Our goal has been to develop a flexible program able to perform nearly any measurement sequence that brings the voltage to a certain value in a given number of steps, what we call a “sequence”. When the program runs, it can be either executing a sequence or maintaining the voltage constant, what we call the “no sequence mode”. In order to perform a sequence, the sequence button (which displays “Start sequence”) should be pressed after having set the following parameters:

- the delay time (see further),
- the voltage to be reached at the end of the sequence,
- the number of steps in the sequence,
Figure 4.27: Summary of the procedure for the high voltage test of GEM foils.

- the ramp slope,
- the landing time.

If the voltage to reach is the same as the present value of the applied voltage or if the difference is lower than 0.01 V, the program automatically returns to its “no sequence mode”, in which a current measurement is performed with a periodicity corresponding to the value of the delay time parameter.

If a sequence is possible, an increasing or a decreasing series of voltage steps will be executed in order to reach the requested voltage. A step is made of a voltage ramp followed by a landing in which the voltage is maintained constant so that the current can stabilize. The voltage ramp is actually a staircase function made of “ministeps”, whose duration we call “miniperiod”.

Also the landing is subdivised in miniperiods (of the same duration). In fact, the real landing time will be the greatest integer multiple of the miniperiod which is lower than the user-set landing time. In every miniperiod of the sequence, first the voltage will be increased by the ministep voltage and then one current measurement will be performed. A sequence automatically stops after the first miniperiod in which the requested voltage is attained or whenever the operator asks it (by pressing the sequence button, that
displayed "Stop sequence" while a sequence is running). The program then automatically switches back to the "no-sequence mode".

The main idea is that the operator should parameterize and launch himself the several sequences for the complete test procedure described in section 4.2.2. If the measured currents are considered too high (e.g. higher than 1 nA in a landing), the operator should press "Stop sequence" and launch a decreasing voltage sequence. The evolution of the test can be followed on a graph of the applied voltage and a graph of the measured current. The mean, the RMS and the median of the current measurements inside a landing are also computed and displayed in real time.

Ending the program is best done using the "Switch off voltage" button, so that the power source will be replaced in stand-by before the run finishes. Note that at the beginning of the program no voltage will be outsourced, so that voltage can only be gradually applied to a GEM foil by launching a given sequence (which will thus start from 0 V). The front panel of the program is shown in Figure 4.28. The main VI uses 14 sub-VIs that we developed for our own needs (cf. Appendix C)

**Number of steps, ramp time, number of ministeps and miniperiod**

At the beginning of a sequence, the program defines the number of steps and then it computes the maximum possible number of ministeps inside one step. The actual number of steps will be equal to the number set by the operator, unless it leads to a step voltage that exceeds a 0.01 V precision. In this case, the number of steps will be set to the greatest integer for which the step voltage does not exceed the 0.01 V precision.

The number of miniperiods in a ramp will be computed as the greatest integer lower than the ramp time divided by the delay time, the ramp time being the step voltage divided by the ramp slope.

The number of ministeps is one more than the number of miniperiods in a ramp, because we consider the miniperiod of the last ministep as being already part of the landing (cf. Figure 4.29).

The ministep voltage is the step voltage divided by the number of ministeps. The miniperiod is the ramp time divided by the number of miniperiods in a ramp (or, in case the latter is zero, the miniperiod is set to the delay time).

There are however two conditions to satisfy:

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1LabVIEW programs are called VIs, which stands for Virtual Instruments.
Figure 4.28: Front panel of the main program for the remote control of the high voltage test.
A miniperiod can not be shorter than the chosen delay time (whose minimum value is 3 ms and precision is 1 ms).

* The ministep voltage, which is the variation of the voltage corresponding to one ministep, can not exceed a 0.01 V precision.

If the first condition is not satisfied, the number of miniperiods in a ramp will be decreased until the two conditions are satisfied. The same will happen in case the obtained ministep voltage is lower than 0.01 V. If the problem is only that the ministep voltage exceeds the 0.01 V precision without being lower than 0.01 V, then first the program tries to increase the number of miniperiods in order to meet the two criteria. If no suitable number is found before the miniperiod becomes smaller than the delay time, then only the program will look for smaller values than the original number of miniperiods in a ramp.

**Remote control and saving options**

The communication between the Keithley 6517B and the computer is achieved through a standard straight-through RS232 cable and is controlled using the VISA application program interface available in LabVIEW. Before running the program, the operator has to select on the front panel the used series port and the baud rate set on the Keithley 6517B. The default baud rate of this instrument is 19200.

The “Save” button allows to start or stop saving the results at any time. However, the two files in which the data are written can be created only once during a single run of the program, so all the data of a run will be written into the same two files. One file contains the current measurements, together with their relative instant of measurement and the corresponding applied voltage.
In the other file, the exact evolution of the applied voltage is recorded (using more points than only those corresponding to current measurements). The operator should select the folder in which the files will be created. The file names are automatically generated, using the date and time at which the run was started and the reference of the GEM foil introduced by the operator.

**Measurement options**

The speed at which the Keithley 6517B performs a current measurement can be selected with the “Integration time” button, which sets the integration time of the analog-to-digital converter, i.e. the period during which the input signal is measured (the aperture). The integration time can be set to 1 or to 2 Power Line Cycles (PLC), 1 PLC being 20 ms (for a 50 Hz power line frequency). It is the responsibility of the operator to select a delay time that is sufficiently long with respect to the time needed for the Keithley 6517B to perform a current measurement and place the entire result in its buffer. In fact, the program uses a parameter, called “DelayForKeithley”, which is the time the program waits between the moment it sends the current measurement request and the moment it reads the contents of the buffer of the instrument. This time is defined as 40% of the user-set delay time (rounded to a 1 ms precision). Working with a 2 PLC integration time will ask for a longer delay time and will thus result in less frequent current measurements. However, the accuracy of the measurements will be higher than if the integration time is 1 PLC. Also the resolution will be better, since the Keithley 6517B is set in the auto-resolution mode, which optimizes the resolution for the present integration time. The resolution will be 5.5 digits for a 1 PLC integration time and 6.5 digits for a 2 PLC integration time.

The program sets the Keithley 6517B in auto-range for the current measurements, because in the high voltage test of GEM foils we can expect values belonging to different current ranges. The drawback of the auto-range mode is that, while searching and switching to the most appropriate range, no current measurements might be made during one or a few miniperiods of the sequence. Therefore, we have included the possibility to speed up the auto-ranging search process by setting a lower and an upper range limit for it, using the two corresponding buttons on the front panel. In case the set lower range is greater than the set upper range, these settings will be ignored and all ranges will be used in the auto-ranging search process.
Finally, the operator can also choose whether to use the built-in 20 MΩ current limiting resistor of the Keithley 6517B. GEM foils in good state have a resistance of at least 100 GΩ, so the protective resistance is be negligible when compared to that value. However, if sparks occur, the current will in any case remain lower than $1000\,\text{V}/20\cdot10^6\,\Omega = 50\mu\text{A}$.

In the present version of the program, the aforementioned measurement options are fixed during a single run of the program, but they already provide a certain flexibility. For the high voltage test, this flexibility as such is not really a requirement, but in an early stage it should help to fine-tune the measurement settings of the Keithley 6517B in the test procedure on GEM foils.
Chapter 5

Conclusion

This thesis has been dedicated to the development of a new tracker of high energy charged particles, based on Gas Electron Multiplier (GEM) chambers. The tracker will operate in high luminosity experiments to be performed in Hall A at Jefferson Lab, where the 12 GeV upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) should be completed in 2014. In particular, the future Super Bigbite Spectrometer (SBS) will possess a Front Tracker composed of two 10 x 20 cm$^2$ silicon strip planes and six 40 x 150 cm$^2$ GEM chambers, identically made up of three adjacent 40 x 50 cm$^2$ triple-GEM modules.

The first part of the original work reported in this thesis is the optimization of the design of the frame that separates two GEM foils of a 40 x 50 cm$^2$ triple-GEM module. Our goal has been to obtain a better spatial uniformity (over the active area of the module) of the continuous Ar-CO$_2$ (70/30) gas flow in the 2 mm gap between two GEM foils, since this gas flow should be spatially uniform in order to guarantee a homogeneous and stable detector response. A finite element study has been performed using the Computational Fluid Dynamics (CFD) add-on package of the COMSOL Multiphysics software. With a frame geometry defined in two dimensions, we have used the built-in Thin-Film Flow Model, which treats the laminar and isothermal flow of a thin fluid film between two large solid structures and solves the corresponding Reynolds equation. We have defined a typical total gas flow of about 3 chamber-volume renewals per hour (60 cm$^3$/min) and this gas flow has been considered incompressible.

The optimization of the frame design has been presented through mainly six simulations, showing progressive modifications of the simulated geometry.
The initially defined geometry corresponds to the first prototype version of the frame, possessing eighteen sectors, two inlets and two outlets. A second simulation has shown that adding a third inlet and a third outlet improves the overall flow uniformity, as the flows in the three six-sector rows become rather independent and similar. High velocity zones nearby inlets and outlets have also been reduced by replacing 90 degrees edges with 1.5 mm radius circular joints. In a third simulation, the number of stagnation zones has been decreased by reducing the number of short spacers from five to three, leading to a frame with twelve sectors which still meets the mechanical requirements related to the planarity of the GEM foils. The fourth simulation, in which openings in the spacers nearby the inlets and outlets have been enlarged from 15 mm to 20 mm, has not yielded a meaningful improvement of the gas flow uniformity. However, the fifth simulation has shown that introducing in the short spacers nine openings of 10 mm, instead of six openings of 15 mm, decreases the size of various stagnation zones. Finally, we have concluded from a sixth simulation that doubling the number of 15 mm openings in the long spacers does not significantly improve the flow uniformity and thus the geometry of the fifth simulation has been selected as the basis for a new frame design. A confirming quantitative analysis of the flow uniformity in the aforementioned simulations has been made using the values of the velocity magnitude in 2000 points located on a rectangular grid. We have compared the extracted velocity distributions of the six simulations through their cumulative frequencies for several fractions of their mean velocity. Due to the linearity of the model, these cumulative frequencies do not depend on the total gas flow. For the ultimately chosen frame design, about 9% of the points have a velocity lower than one half of the mean velocity (against 19 to 20% for the original frame design) and also about 9% of the points have a velocity greater than 1.5 times the mean velocity (against nearly 15% for the original frame).

In the simulation of the chosen frame design, a small value (0.1642 Pa for a total flow of 60 cm$^3$/min) has been obtained for the total pressure loss across the module. This simulation has also indicated that the inlets and outlets are responsible of a very large fraction of the total pressure loss. In order to confirm whether it is advantageous to connect in series the gas systems of the three modules of a chamber, we consider that it would be useful to make a three-dimensional model of the frame which accurately evaluates the pressure losses across a single module.
The second part of the reported original thesis activities concerns the development of a LabVIEW program for the remote control of the high voltage test of GEM foils, which belongs to the quality check procedures of the manufacturing process of a GEM module. After having given an overview of the assembling method of such a module, we have explained the quality checks that will be performed on GEM foils, i.e. the optical inspection and the high voltage test. Especially the latter, in which the leakage current through the Kapton layer of the foil is measured when a voltage is applied between the external copper layers, plays a crucial role in indicating the presence of problematic manufacturing defects in GEM foils. In Catania, an electrometer Keithley 6517B will be used to both apply the voltage and measure the leakage current. The LabVIEW program that has been developed for its remote control, has been given a large flexibility. It is able to generate increasing as well as decreasing voltage sequences, made up of “steps” that each consist of a voltage ramp followed by a landing. It also periodically triggers and retrieves current measurements, during a sequence but also while the applied voltage remains constant in between sequences. A sequence can be launched or aborted at any time and, apart from the number of steps and the voltage to reach, the operator can also select the ramp slope, the landing time and the “delay time” (representative of the period in between two current measurements, at least if the chosen combination of the parameters does not lead to voltage increments that exceed the 0.01 V precision). Based on the inserted parameters, the program automatically maximizes the number of voltage increments which constitute a ramp. Additional fine-tuning of the high voltage test can be achieved through the adjustment of the integration time of the electrometer’s analog-to-digital converter (to 1 or 2 Power Line Cycles) and the selection of the lower and upper range limits for the auto-ranging search process. Moreover, the operator can choose whether to use the built-in 20 MΩ current limiting resistor of the Keithley 6517B, as a protection for the GEM foil. The evolution of the applied voltage and the measured current can be followed on displayed graphs and are also recorded in text files on request.
Appendix A

The previous and the latest GEM frame designs

All the presented CAD drawings have been produced by Ing. Francesco Noto. Figures A.1 to A.4 show the first frame design used for the gas flow simulations presented in this thesis (i.e. Simulation 1). The frame design that has been produced after having taken into account the results of these gas flow simulations, is shown in Figures A.5 to A.8.
Figure A.1: Previous design – all frames of the module assembled
Figure A.2: Previous design – the GEM frame
Figure A.3: Previous design – the GEM frame (3D side view)
Figure A.4: Previous design – a gas inlet/outlet of the GEM frame
Figure A.5: Latest design – all frames of the module assembled
Figure A.6: Latest design – the GEM frame
Figure A.7: Latest design – a gas inlet/outlet of the GEM frame

Figure A.8: Latest design – a gas inlet/outlet of the GEM frame (3D view)
Appendix B

Reichenberg’s formula for the dynamic viscosity of a gas mixture

Reichenberg’s “simplified formula” [75] allows to compute the dynamic viscosity of a gas mixture. In this appendix, we give the intermediate calculations needed for this formula, using the following symbols:

- $T$ the considered temperature
- $p$ the considered pressure
- $\mu$ the dynamic viscosity of the gas mixture
- $\phi_i$ the volume fraction of component $i$
- $\mu_i$ the dynamic viscosity of component $i$
- $M_i$ the molecular mass of component $i$
- $m_i$ the dipolar momentum of component $i$
- $Z_i$ is the compressibility factor of component $i$ ($Z=1$ for an ideal gas)
- $T_{ci}$ the critical temperature of component $i$
- $p_{ci}$ the critical pressure of component $i$
- $n$ the total number of components in the mixture

The reduced temperature and pressure of component $i$ are given by:

$$T_{ri} = \frac{T}{T_{ci}}, \quad \text{(B.1)}$$

$$p_{ri} = \frac{p}{p_{ci}}. \quad \text{(B.2)}$$

The reduced dipole momentum of component $i$ is given by:

$$m_{ri} = 52.46\frac{p_{ci}}{T_{ci}}m_i. \quad \text{(B.3)}$$
Then the following coefficients are calculated for each component:

\[ F_i = \frac{T_{r_i}^{3.5} + m_{r_i}^7 \cdot 10^7}{T_{r_i}^{3.5} + T_{r_i}^{3.5} \cdot m_{r_i}^2 \cdot 10^7} \]  
\( \text{(B.4)} \)

\[ U_i = \frac{F_{r_i}}{\sqrt{T_{r_i}}} \left(1 + 0.36T_{r_i}(T_{r_i} - 1)\right)^{1/6} \]  
\( \text{(B.5)} \)

\[ C_i = \frac{M_i^{1/4}}{\sqrt{\mu_i}U_i} \]  
\( \text{(B.6)} \)

\[ y_i = \frac{\phi_i/Z_i}{\sum_i(\phi_i/Z_i)} \]  
\( \text{(B.7)} \)

Hereafter, one computes the following coefficients for each couple of components \( i \) and \( j \):

\[ T_{r_{ij}} = \frac{T}{\sqrt{T_{c_i}T_{c_j}}} \]  
\( \text{(B.8)} \)

\[ m_{r_{ij}} = \sqrt{m_{r_i}m_{r_j}} \]  
\( \text{(B.9)} \)

\[ F_{r_{ij}} = \frac{T_{r_{ij}}^{3.5} + m_{r_{ij}}^7 \cdot 10^7}{T_{r_{ij}}^{3.5} + T_{r_{ij}}^{3.5} \cdot m_{r_{ij}}^2 \cdot 10^7} \]  
\( \text{(B.10)} \)

\[ U_{ij} = \frac{F_{r_{ij}}}{\sqrt{T_{r_{ij}}}} \left(1 + 0.36T_{r_{ij}}(T_{r_{ij}} - 1)\right)^{1/6} \]  
\( \text{(B.11)} \)

\[ H_{ij} = U_{ij}(C_i + C_j)^2 \sqrt{\frac{M_iM_j}{32(M_i + M_j)^3}} = H_{ji} \]  
\( \text{(B.12)} \)

For each component \( i \), one should then compute the following coefficients:

\[ D_i = \sum_{k=1, k\neq i}^n y_k H_{ik}(3 + 2 \frac{M_k}{M_i}) \]  
\( \text{(B.13)} \)

\[ K_i = \frac{y_i \mu_i}{y_i + \mu_i D_i}, \]  
\( \text{(B.14)} \)
APPENDIX B. REICHENBERG’S FORMULA

\[ A_i = \sum_{j=1}^{i-1 \neq 0} H_{ij} K_j \quad (A_1 = 0) \tag{B.15} \]

\[ B_i = \sum_{j=1 \neq i}^{n} \sum_{k=1 \neq i}^{n} H_{ij} H_{ik} K_j K_k \tag{B.16} \]

Finally, the dynamic viscosity of the gas mixture is given by:

\[ \mu = \sum_{i=1}^{n} K_i (1 + 2A_i + B_i). \tag{B.17} \]

Example:
Dynamic viscosity of a Ar-CO\(_2\) (70/30) mixture at 20°C and 1 atm.
The used parameters are given in Table 4.1 on page 73.
Used indices: i=1 for Ar and i=2 for CO\(_2\).

\[ T_{r1} = 1.9421981; \quad T_{r2} = 0.9634355; \tag{B.18} \]
\[ p_{r1} = 0.0206870; \quad T_{r2} = 0.0137409; \tag{B.19} \]
\[ m_{r1} = 0; \quad m_{r2} = 0; \tag{B.20} \]
\[ F_{r1} = 1; \quad F_{r2} = 1; \tag{B.21} \]
\[ U_1 = 0.7807007; \quad U_2 = 1.0166345; \tag{B.22} \]
\[ C_1 = 106.5275482; \quad C_2 = 119.3359289; \tag{B.23} \]
\[ y_1 = 0.6989244; \quad y_2 = 0.3010756; \tag{B.24} \]
\[ T_{r12} = T_{r21} = 1.3679117; \tag{B.25} \]
\[ m_{r12} = m_{r21} = 0; \tag{B.26} \]
\[ F_{r12} = F_{r21} = 1; \tag{B.27} \]
\[ U_{12} = U_{21} = 0.8790701; \tag{B.28} \]
\[ H_{12} = H_{21} = 13663.7716767; \tag{B.29} \]
\[ D_1 = 121405.75; \quad D_2 = 45986.85; \tag{B.30} \]
$K_1 = 0.0000133; \quad K_2 = 0.0000045;$ \quad (B.31)

$A_1 = 0; \quad A_2 = 0.1822980;$ \quad (B.32)

$B_1 = 0.0037966; \quad B_2 = 0.0332326;$ \quad (B.33)

$\mu = 1.9696 \cdot 10^5 Pa \cdot s$ \quad (B.34)
Appendix C
Sub-VIs of the LabVIEW program for the remote control of the high voltage test

The sub-VIs developed for the main VI (0_GEM_foil_QualityCheck.vi), used for the remote control of the high voltage test of GEM foils, are the following:

1. write_readbuffer.vi: sends a command to the Keithley 6517B and reads the response placed in its buffer after having waited for a specified delay.

2. BuildFilePaths.vi: uses the folder path, the reference of the GEM foil and the Date/Time string to generate the paths of the files in which the voltages and the currents are saved.

3. GetPresentTime.vi: computes the time that has elapsed since the actual test procedure has begun. The latter begins after all initial configuration steps have been executed.

4. Fetch_Current.vi: calls write_readbuffer.vi in order to perform a current measurement. The delay time between the measurement request and the reading in the buffer is set to the value of the parameter “DelayForKeithley”.

5. ConvertStringToNumber.vi: this sub-VI is used to read the string in the buffer of the Keithley 6517B and to convert it into a numerical value without any precision loss.
APPENDIX C. SUB-VIS OF THE HV TEST LABVIEW PROGRAM

6Refresh_CurrentGraph.vi: adds a point on the displayed graph of the current as a function of the time returned by 3_GetPresentTime.vi.

7_InitFiles.vi: creates the two files in which the results will be saved and also writes the GEM foil reference, the date and time at which the run was launched (i.e. the Date/Time string) and the title of the columns at the beginning of these files.

8_Procedure_A.vi: this sub-VI first calls 3_GetPresentTime.vi and 4_Fetch_Current.vi simultaneously, followed by 5_ConvertStringToNumber.vi and 6_Refresh_CurrentGraph.vi. Then, it turns the Measurement?-indicator on for 100 ms, meanwhile it checks whether the Save?-button is on. If so, it checks whether the files have already been initialized (if not, it calls 7_InitFiles.vi) and then writes the present time, the applied voltage and the current into the current file.

9_RoundToPrecisionE-3.vi: rounds a value to a precision of $10^{-3}$; is used to round time intervals to a millisecond precision.

10_Refresh_VoltageGraph.vi: adds a point on the displayed graph of the voltage as a function of the time returned by 3_GetPresentTime.vi.

11_Procedure_B.vi: calls 3_GetPresentTime.vi, followed by 10_Refresh_VoltageGraph.vi. Then, it checks whether the Save?-button is on. If so, it checks whether the files have already been initialized (if not, it calls 7_InitFiles.vi) and then writes the present time and the applied voltage into the voltage file.

12_Set_Voltage.vi: calls 1_write_readbuffer.vi in order to set the requested value of the voltage source (but does not control the outsourcing of this voltage).

13_Update_ArrayLanding.vi: this sub-VI is called when the voltage is in a “landing” in order to add the last value of the measured current to the array whose values are used to compute the voltage mean, RMS and median over the “landing”. 
14. ExceedsPrecisionE-2.vi: is used to check whether a given voltage exceeds a 0.01 V precision (if so, it returns True).
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