Optimization of the operating parameters of the LHCb muon system

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Abstract

LHCb is a $B$ physics experiment at the Large Hadron Collider (LHC) at CERN. The LHCb muon detector has a total area of about 435 m$^2$ and is divided into five stations with four regions of different granularity. The whole system is composed of 1380 Multi Wire Proportional Chambers (MWPCs). To obtain a good trigger performance each chamber should have an efficiency of approximately 99% which translates into a time resolution $< 3.5$ ns r.m.s..

To achieve the required efficiency and time resolution the muon chambers have to be operated at the lowest possible threshold. To minimize ageing effects at the same time the chambers have also to be operated at the lowest possible voltage. In order to optimize the operating parameters of the muon system it is of particular importance to have a profound understanding of the effects that limit the performance.

This work describes a detailed study of all the resolution limiting parameters of the MWPCs in order to find out how they contribute to time resolution and therefore affect the threshold settings. The study was carried out using the drift chamber simulation program GARFIELD [1]. The simulations have been compared with actual measurements to ensure that the simulation reproduces the measurement well. It was of particular interest to understand the dependence of time resolution and efficiency on electronics noise and threshold. The simulation study showed that charge deposit fluctuations have a big influence on time resolution because of the time slewing effect. The effect of a time slewing correction is shown.

Since ageing will not play a role during the first phase of operation with LHC beams, one should concentrate first of all on the threshold settings. Therefore an optimization of the electronics thresholds for the different chamber types was performed using the information obtained by the simulations. In this context, the noise characteristics of the
front-end (FE) electronics have been studied. The threshold settings of the past were improved by setting individual thresholds for the 122k FE channels of the muon system. It is shown that the thresholds keep the noise in the system at an acceptable level while conserving time resolution and efficiency. Knowing this one can now start to optimize the high voltage settings.

The last chapter finally concentrates on the presentation of results obtained by analysing cosmics data and first collision data acquired in LHCb to get a first overview of the performance of the muon system with the final threshold settings.
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From Werner Riegler I learned a lot about detector physics and electronics. He was the first who introduced me to the GARFIELD simulation program. Whenever I didn’t understand the outcome of some simulation and didn’t know how to proceed, he was the one who answered my questions and found an explanation for the results and a way to carry on. Thanks a lot for the support.

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Chapter 1

$B$ physics at LHC

The Large Hadron Collider beauty (LHCb) experiment at CERN is the first dedicated $B$ physics experiment at a hadron collider. It is optimized to study particles containing $b$ quarks and will search for new physics beyond the Standard Model (SM) by exploiting the CP violating and rare decays of $B$ mesons. The violation of CP symmetry beyond the SM could solve fundamental problems of modern physics like the baryon asymmetry in the universe which is not yet explained. Since $B$ physics seems to be the most promising approach to find new physics in this field it attracted more and more attention during the last decades. $B$ factories like BaBar at SLAC or BELLE at KEK and the Tevatron experiments CDF and D0 have been already operating since years making new discoveries in physics [2]. The experiments at the LHC, in particular LHCb, will be able to enter a new era of $B$ physics.

1.1 CP violation and the CKM matrix

There are three fundamental symmetry operations in physics [3]: the particle-antiparticle conjugation or charge conjugation, the parity transformation and the time inversion. Up to now no process in nature has been observed which violates the CPT symmetry. So the product of all three operations is conserved. But it turned out that charge conjugation and parity are always violated in weak interaction processes. In 1964 Cronin, Fitch,
Figure 1.1: One of the six Unitary Triangles corresponding to $V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$.

Christenson and Turlay proved that the combined operation CP is also violated in certain processes [2]. Since the CPT symmetry is conserved this implies that whenever the CP symmetry is broken the time reversal must also be violated.

In the Standard Model (SM) the CP violation is based on the quark mixing which is described by a unitary matrix called Cabibbo-Kobayashi-Maskawa (CKM) matrix [2]. It describes the coupling between up-type quarks ($u, c, t$) and down-type quarks ($d, s, b$).

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (1.1)$$

The CKM matrix can be parameterized by three Euler angles and one complex phase [4]. The most common parametrization was introduced by Wolfenstein. The CP violation enters the SM through the complex phase $\eta$.

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \quad (1.2)$$

By using the unitarity of the CKM matrix six equations can be found. One of them is

$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0 \quad (1.3)$$

The six relations can be represented as triangles in the complex plane. These triangles are called Unitary Triangles (UT) and they all have the same area. Relation 1.3 after
normalization is shown in Fig. 1.1. This UT with sides of approximately the same length and therefore angles $>> 1$ is very important when studying CP violation in $B$ meson system.

There are in general three methods which can be used to search for new physics in $B$ decays [2].

1. **Measurement of the angles and sides of the CKM triangles.** The goal is to measure the quantities very precise and through different processes and look for different results where the SM predicts equality.

2. **Look for new physics in quark mixing.** In particular, one can use the $B_s$ to search for inconsistencies in the SM. CP violation in $B_s$ mixing is well explained in the SM but it seems that the $B_s$ mixing phase is much larger than predicted.

3. **Search for new physics in rare $B$ decays** which are suppressed in the SM. If loop diagrams are involved in decay processes there could be new particles predicted by Super Symmetry (SUSY) for example that influence the decay characteristics.

Table 1.1 summarizes the interesting quantities for new physics and how they can be measured [2].

<table>
<thead>
<tr>
<th>Table 1.1: Main measurements to determine the CKM matrix with $B$ decays.</th>
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<tbody>
<tr>
<td><strong>Quantity</strong></td>
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<tr>
<td>$\sin(2\alpha)$</td>
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<tr>
<td>$\cos(2\alpha)$</td>
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<tr>
<td>$\text{sign}(\sin(2\alpha))$</td>
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<td>$\sin(2\beta)$</td>
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<tr>
<td>$\cos(2\beta)$</td>
</tr>
<tr>
<td>$\Delta\Gamma$ for $B_s$</td>
</tr>
</tbody>
</table>
1.2 LHCb - A dedicated $B$ physics experiment at LHC

The Large Hadron Collider (LHC) at CERN is a proton-proton collider with a center of mass energy of 14 TeV. The $b\bar{b}$ production cross section $\sigma_{b\bar{b}}$ will be $\approx 500 \mu b$ which makes the LHC the most copious source of $B$ mesons world wide. At a moderate luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ at LHCb $10^{12} b\bar{b}$ pairs will be created in one year ($10^7 \text{ s}$). This high production rate offers perfect conditions for studying $B$ physics.

The LHCb detector has to fulfill all the main requirements to do high precision physics at LHC. Firstly, the detector has to be optimized for high rate capability to be able to work in a high luminosity environment with maximum efficiency for a long period of time. A strong magnetic field is needed to do good momentum measurement. A precise vertex system must be able to reject background and measure oscillations and lifetime differences in the $B_s$ system. Particle identification is another main requirement for LHCb. In order to reconstruct many $B$ meson final states it is crucial to clearly identify and distinguish kaons and pions. Besides, the detection of muons, electrons, photons, $\pi^0$’s and $\eta$’s is very important. In addition a very efficient, robust and fast trigger and data acquisition system are fundamental requirements. The LHCb detector which is described in more detail in section 2.2 merges all these important ingredients and will be able to search for new physics beyond the SM [5].
Chapter 2

The LHCb detector at LHC

The Large Hadron Collider beauty (LHCb) experiment is a dedicated $B$ physics experiment installed at the Large Hadron Collider (LHC) at CERN. The LHCb experiment will look for new physics in CP-violation beyond the Standard Model by studying particles containing $b$ quarks.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a circular proton-proton collider with a circumference of approximately 27 km located at the European Organisation for Nuclear Research (CERN). The LHC is installed about 100 m underground in a tunnel which had been used for an electron-positron collider called LEP in the past. The design luminosity of the LHC is $\mathcal{L} = 10^{34}$ cm$^{-2}$s$^{-1}$ and the nominal center of mass energy for collisions is 14 TeV. The two circulating proton beams consist of 2808 bunches with about $10^{11}$ protons each and are separated by 25 ns. The beams are kept on the circular trajectory by 9300 superconducting magnets cooled to 1.9 K. The energy of 7 TeV per beam is limited by the 8.34 T magnetic field strengh of the 1232 dipole bending magnets. With a proton-proton cross section of approximately 100 mb one can expect about 20 proton-proton collisions per bunch crossing at the nominal luminosity $10^{34}$ cm$^{-2}$s$^{-1}$. At LHCb the luminosity will be limited to $\mathcal{L} = 2 - 3 \times 10^{32}$ cm$^{-2}$s$^{-1}$ in order to reduce the number of multiple
interactions per bunch crossing.

Before the protons are injected into the LHC they pass through a chain of accelerators of different types and sizes. The whole CERN accelerator complex is shown in Fig. 2.1. The protons which are obtained by removing electrons from hydrogen atoms are passing through a linear accelerator called LINAC 2 and are injected into the booster at an energy of 50 MeV. In this first circular accelerator the protons are further accelerated up to 1.4 GeV before they are directed to the Proton Synchrotron (PS) which they leave with 26 GeV for the Super Proton Synchrotron (SPS). Via two injection lines (TI 2 and TI 8) the two proton beams are injected with 450 GeV energy into the LHC accelerator, where they finally reach the maximal energy of 7 TeV. Four experiments, namely ATLAS, CMS, LHCb and ALICE, are located at four interaction points around the LHC where the two proton beams are brought to collision. ATLAS and CMS are general purpose experiments

![Figure 2.1: The figure shows the whole CERN accelerator complex. The protons are accelerated by LINAC 2, the booster, PS and SPS before they are injected into the LHC.](image-url)
that will search for new physics at the energy frontier. Their goals are for example the detection of the Higgs boson or the study of Super Symmetry (SUSY). One of the physics goals of ALICE is to study the quark-gluon plasma expected in the early universe. The view of the location of the LHC and of the experiments is shown in Fig. 2.2.

2.2 The LHCb experiment

2.2.1 Detector layout

The LHCb detector is a single-arm spectrometer with an angular acceptance of 10 mrad to 300 mrad (250 mrad) in the bending (non bending) plane. The layout is justified by the fact that $B$ mesons are produced predominantly in the same forward and backward region at polar angles around zero and $\pi$ respectively (Fig. 2.3). Fig. 2.4 shows a side view of the detector. The LHCb experiment is situated at the LHC Intersection Point 8 in the cavern where the DELPHI experiment was installed during LEP operation.
The detector is composed of several subsystems. Their location along the beam axis is shown in Fig. 2.4. Most of the subsystems consist of two detector halves which can be moved away from the beam axis for assembly and maintenance and to provide access to the beam pipe. The main subsystems are:

- the vertex locator system (VELO)
- the tracking system (TT, T1, T2 and T3) and the spectrometer magnet
- the Ring Imaging Cherenkov counters (RICH-1 and RICH-2)
- the calorimeter system (SPD, PS, ECAL, HCAL)
- the muon system (M1 to M5)

2.2.2 VELO

The purpose of the VELO or VErtex LOcator system [6] is to measure very precisely the tracks of charged particles resulting from $b$ hadron decays very close to the beam pipe. The vertex locator is the first tracking device of the LHCb experiment, positioned before
Figure 2.4: Side view of the LHCb detector.
The VELO consists of several stations of silicon strip detectors with circular and radial strips in order to measure the radial ($r$) and azimuthal ($\phi$) component of the tracks. The stations are positioned perpendicular to the beam pipe and each station is composed of two half-moon shaped planes, one on each side of the proton beam. While the silicon sensors are positioned at a distance of only 7 mm from the beam during data taking, the stations are moved away from the beam mechanically during beam injection and phases of instable beam in order to prevent the system from damages. The VELO system is placed inside the LHC vacuum system in order to keep the distance to the interaction point and the amount of material in between as small as possible. The silicon sensors are just separated from the beam vacuum by a thin aluminium foil. An overview of the VELO system is shown in Fig. 2.5.

### 2.2.3 RICH counters

Reliable particle identification is a main requirement of the LHCb experiment. In particular one has to separate pions from kaons in $B$ meson decays to reduce the background from...
Figure 2.6: The left plot shows a side view of RICH-1 which covers the full LHCb acceptance and a momentum range from 1 to approximately 65 GeV/c. On the right side one can see the schematic of the HPDs used in the RICH counters.

\[ B_d \rightarrow K^\pm \pi^\mp, \ B_s \rightarrow K^\pm \pi^\mp \ \text{and} \ B_s \rightarrow K^\pm K^\mp. \]  

The Ring Imaging Cherenkov counters (RICH) [6] used in the LHCb experiment provide particle identification in a momentum range from 1 to 100 GeV/c and beyond.

Since the momentum spectrum is soft at large polar angles and harder at small polar angles a system of two RICH detectors is needed to cover the full momentum range. RICH-1 is placed upstream of the LHCb dipole magnet and covers the full LHCb acceptance. It detects particles in a momentum range of 1 to approximately 65 GeV/c. RICH-2 can identify particles with momenta up to 100 GeV/c and more and is situated downstream of the magnet and the tracking stations T1, T2 and T3. The angular acceptance of RICH-2 is limited. In RICH-1 aerogel and C\(_4\)F\(_{10}\) gas are used as radiators to detect low-momentum particles while RICH-2 uses a CF\(_4\) radiator to cover the high-momentum range. In both detectors a system of flat and spherical mirrors is used to focus the Cherenkov light and to reflect it out of the LHCb detector acceptance onto an array of Hybrid Photon Detectors (HPDs) which allow to detect the Cherenkov Photons in a wavelength range from 200 to...
600 nm. A side view of RICH-1 is shown in Fig. 2.6 as well as a schematic of the HPDs.

### 2.2.4 Trackers and magnet

A reliable tracking system is very crucial for each of the LHC experiments to reconstruct the tracks of charged particles in order to measure their momenta and to provide information for other parts of the experiment.

The tracking system of the LHCb experiment [6] consists of four stations. The Trigger Tracker (TT) is located between the RICH-1 detector and the experiments dipole magnet and covers the full acceptance of the system. The other three stations (T1, T2 and T3) are situated downstream of the magnet before RICH-2 and are divided into an inner region called Inner Tracker (IT) and an outer region, the Outer Tracker (OT). An overview of the tracking system is shown in Fig. 2.7. The LHCb tracking system comprises two different detector types. The Outer Tracker uses straw-tube drift chambers with a tube diameter of 5 mm to detect charged particles while in the Trigger Tracker and in the Inner Tracker silicon microstrip detectors with 200 µm strip pitch are implemented.

The magnet of the LHCb experiment [6] is situated near the interaction point and covers an angular range of ± 250 mrad vertically and ± 300 mrad horizontally. A warm dipole magnet is used at present to bend the tracks of charged particles in order to measure their momenta. Since a momentum resolution of 0.4 % for tracks up to 200 GeV/c is required in the LHCb experiment an integrated magnetic field of 4 Tm is needed.

### 2.2.5 Calorimeters

The LHCb calorimeter system [6] has three main purposes. It will trigger on electrons, photons and hadrons, it will measure energies and positions of traversing particles and it will identify photons and neutral pions to study specific $B$ meson decays.

The whole system is built up of several layers: the Scintillating Pad Detector (SPD), the Pre-Shower (PS), the Electromagnetic Calorimeter (ECAL) and the Hadron Calorimeter.
Figure 2.7: The plot shows an overview of the LHCb tracking system which consists of the Trigger Tracker (TT) and the three stations T1, T2 and T3 which are divided into an inner region (IT) and an outer region (OT).

(HCAL) (Fig. 2.4). The SPD and the PS are situated upstream of the ECAL and HCAL and determine the charge (charged or neutral) and the electromagnetic character of traversing particles. Both, the ECAL and the HCAL, consist of an assembly of alternating metal and scintillation plates. Furthermore all calorimeters are based on the same principle: the produced scintillation light is guided to a Photo-Multiplier (PMT) using wavelenght shifting fibers (WLS). In the SPD/PS system multi-anode photo-multiplier tubes are used to read out the fibers while for the ECAL and HCAL individual phototubes are needed.

2.2.6 Muon system

Since muons are present in the final states of many CP-sensitive $B$ decays, muon triggering and muon offline identification are fundamental requirements of the LHCb experiment.

The LHCb muon system [6, 7] is divided into five stations (M1-M5) of rectangular shape placed around the beam pipe. M1 is situated before the SPD, the other four stations
The luminosity at LHCb is limited to $2 - 3 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ in order to have mainly single interactions.

M2-M5 are located behind the calorimeters. The stations are separated by a muon filter consisting of the calorimeter and four iron absorbers, each 80 cm thick. The minimum momentum a muon must have in order to cross all five station is approximately 6 GeV/c. The main detector technology used in the muon system is the Multi Wire Proportional Chamber (MWPC) [6]. They are used in all the stations, only in the inner region of M1 Triple-GEM detectors [8] are installed. Fig. 2.9 shows a side view of the LHCb muon system which will be described in more detail in section 2.3.

### 2.2.7 Trigger system

The luminosity in the LHCb interaction region is limited to $\mathcal{L} = 2 - 3 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$. This has two advantages. Firstly, the event rate is mainly dominated by single interactions (Fig. 2.8) which are easier to analyse and secondly, the radiation damage is lower. The LHC bunch crossing rate inside the LHCb detector is 40 MHz but as one can see from Fig. 2.8, the rate of events from pp-collisions at the moderate luminosity of LHCb is only about 10 MHz. Regarding the fact that this rate has to be reduced to 2 kHz because of data storage reasons and the fact that the $B$ decays interesting for new physics are very rare, one can understand that a reliable and efficient trigger system is crucial for the
The trigger system used in the experiment [6] is divided into two levels: Level Zero (L0) and High Level Trigger (HLT).

1. **Level 0:** The L0 trigger reduces the event rate from 40 MHz to 1 MHz in a latency of only 4 µs. To achieve this goal, L0 uses information from other subdetectors of LHCb. The VELO pile up system provides information about the number of pp-collisions. Events with multiple proton-proton interactions are rejected. Since particles from $B$ decays have higher transverse momenta $p_T$ than particles resulting from so called minimum bias events, only these events are selected by the trigger by using the information of the calorimeter (electrons, photons, hadrons with high $E_T$) and muon system (muons with high $p_T$).

2. **High Level Trigger:** The HLT runs offline and uses more time to decide if an event is rejected or not. The HLT is again divided into two sublevels called HLT1 and HLT2. The HLT1 confirms if the selection done by the L0 trigger is justified or not by using further information of the VELO and the tracking system. In particular it looks for displaced secondary vertices in the VELO. The HLT1 reduces the rate to less than 100 kHz. The HLT2 then reduces the event rate to the demanded 2 kHz by performing a full event reconstruction of $B$ decays using all the subdetectors of the system.

### 2.2.8 Online system

The main purpose of the LHCb online system [6] is to monitor and control the data transmission from the on/near detector electronics (front-end electronics) to the final storage. The online system ensures that this data transfer is accomplished correctly and under controlled and known conditions. Furthermore the online system supervises the timing of the whole detector in the sense of synchronizing the subdetectors with the LHC clock.
The online system is in principle divided into three subsystem which run in parallel:

- the Data Acquisition (DAQ) system ensures a safe data transfer from the detector electronics to the final storage. L0 triggered data is sent from the front-end electronics into the LHCb readout boards (TELL1s). After further processing they are transferred to a CPU farm where the HLT selects interesting events which are finally stored in the CERN CASTOR facility. From there the raw data are distributed in quasi real time to six Tier-1 centres across Europe.

- the Timing anf Fast Control (TFC) system plays an important role in the data readout between the front-end electronics and the online processing farm since it synchronizes trigger decisions and beam-synchronous commands to the LHC clock and orbit signal provided by the LHC.

- the Experiment Control System (ECS) monitors the other system described above and the state of the whole detector. This means that the ECS controls not only the TFC system, the DAQ system and the trigger but also the operational parameters of the sub-detectors like HV and LV, pressures, gas flows and temperatures.

2.3 The LHCb muon system

To achieve the physics goals of the LHCb experiment it is fundamental to have an efficient and reliable muon system. Muons are present in the final states of many CP-sensitive $B$ decays. The two decays which are of particular interest are $B^0 \rightarrow J/\psi(\mu^+\mu^-)K^0_s$ and $B^0_s \rightarrow J/\psi(\mu^+\mu^-)\phi$. Furthermore muons from semi-leptonic $b$ decays provide a flavour tag of accompanying neutral $B$ mesons. In addition rare decays such as the flavour changing neutral current decay $B^0_s \rightarrow \mu^+\mu^-$ have muons in the final states and may open the way to new physics.
2.3.1 System requirements

Physics requirements

The main purposes of the muon system are to provide

- a fast and reliable trigger on high $p_T$ muons. A time resolution better than 25 ns is required in the trigger to unambiguously identify the bunch crossing.

- an efficient offline muon identification. Muons reconstructed in the tracking system have to be identified correctly with an efficiency above 90 % and a misidentification rate < 1.5 %.

Background

The detector efficiency is mainly limited by the large background due to charged and neutral particles expected in the muon system. The large flux of particles imposes stringent requirements like rate capability of the chambers, ageing characteristics of the detector and redundancy of the trigger. The main background in the muon system comes from:

- Decay muons which result from the large number of $\pi/K$ mesons that decay during their flight and which form the main background in the L0 muon trigger.

- Shower particles which are generated either by photons that interact close to the beam pipe and produce electromagnetic showers or by hadrons which interact late in the calorimeters and contribute through shower muons or hadron punch-through.

- Low-energy electrons which are mainly created through neutron reactions.

- Beam halo muons which can traverse the detector in the same direction as particles from the interaction point.

The expected particle rates in the muon system have been calculated using the simulation packages GCALOR and MARS [7] and are listed in Table 2.3.
Detector requirements

The LHC bunch crossing rate of 40 MHz and the intense particle flux in the muon system impose challenging requirements on the detectors in terms of:

- Rate capability and ageing: The chambers should be operated for 10 years at the nominal luminosity of $2 - 3 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ with a gas gain of $10^5$. In this time the muon chambers will be exposed to particle rates up to 0.2 MHz/cm$^2$ in the inner regions. The total accumulated charge will be about 1.5 C/cm$^2$ on the cathodes and 0.44 C/cm on the wires in the inner regions.

- Time resolution: To achieve the required trigger efficiency of at least 95 % each muon station should have an efficiency higher than 99 % which means that each double gap should have a time resolution $< 3.5$ ns.

- Spatial resolution: The transverse momentum $p_T$ of traversing muons must be determined with a resolution of 20 %.

2.3.2 Overview

The LHCb muon system [6, 7] consists of five stations M1-M5 (Fig. 2.4). The stations are of rectangular shape and are placed along the beam axis. While station M1 is located before the calorimeters in order to improve the $p_T$ measurement in the trigger the other four stations are situated downstream of the calorimeter system. Stations M2-M5 are separated by iron filters, each 80 cm thick, to select muon candidates. The whole muon filter including the calorimeters has a total thickness of about 20 interaction lengths and therefore a momentum of at least 6 GeV/c is needed for a muon to traverse all five stations. The whole muon system consists of 1380 chambers to detect traversing particles in an inner and outer angular acceptance of 20 (16) mrad and 306 (258) mrad in the bending (non-bending) plane. The total detector covers an area of 435 m$^2$. Fig. 2.9 shows a side view of the muon system.
Each muon station is divided into 4 regions starting from the beam pipe to the outside. Fig. 2.10 shows one quadrant of muon station M2. The different regions R1-R4 are indicated. The four regions provide different granularity to keep the particle rate and the occupancy roughly the same over one station.

2.3.3 Detectors

The detectors used in the LHCb muon system are optimized for fast triggering and redundancy. Multi Wire Proportional Chambers (MWPCs) [6] are used for most parts of the system. Only in region 1 of station M1 where the particle rate is very high Triple-GEM (Gas Electron Multiplier) detectors [8] have been installed because of better ageing properties. The chambers consist of two or four OR-ed gas gaps, depending on the station. In stations M2-M5 the chambers have four gaps arranged in two independent layers with separate readout to achieve maximum redundancy. In station M1 the chambers only have
two gaps to reduce the amount of material in front of the calorimeter. Here each single gap is readout separately. Each double gap should have an efficiency of at least 95 %. However, the system will be much more stable and redundant with a double gap efficiency of 99 % which translates into a time resolution < 3.5 ns.

The MWPCs consist of a wire plane with 2 mm wire spacing (wire pitch) placed symmetrically in a 5 mm gap filled with a Ar, CO₂ and CF₄ gas mixture in the ratio of 40/55/5. The gas flows serially through all the gaps of one chamber. In order to achieve the required time resolution and efficiency the chambers are operated at voltages up to 2650 V. The gas gain G at a voltage of 2.65 kV is \( \approx 10^5 \) and doubles approximately every 100 V. In order to decrease ageing in the future the goal is to lower the high voltage and to reach a gas gain of \( \approx 5 \times 10^4 \). Each gap has a separate high voltage line in order to maximize the
Table 2.1: Main MWPC parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of gaps</td>
<td>4 (2 in M1)</td>
</tr>
<tr>
<td>Gas gap thickness</td>
<td>5 mm</td>
</tr>
<tr>
<td>Wire spacing</td>
<td>2 mm</td>
</tr>
<tr>
<td>Wire</td>
<td>Gold-plated Tungsten 30 µm diameter</td>
</tr>
<tr>
<td>Wire length</td>
<td>250 to 310 mm</td>
</tr>
<tr>
<td>Wire tension</td>
<td>0.7 N</td>
</tr>
<tr>
<td>Total no. of wires</td>
<td>≈ 3 · 10^6</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>2.65 kV</td>
</tr>
<tr>
<td>Gas mixture</td>
<td>Ar/CO_2/CF_4 40/55/5</td>
</tr>
<tr>
<td>Gas Gain</td>
<td>≈ 10^5 @ 2.65 kV</td>
</tr>
</tbody>
</table>

Figure 2.11: The figure shows a cross section of a chamber with four gaps. Two adjacent gaps are OR-ed and form a so called double gap. The plane of wires with 2 mm wire spacing is placed symmetrically between the cathode planes which are segmented into pads to fulfill the requirements of spatial resolution.

redundancy of the system. The main chamber parameters are listed in Table 2.1. Fig. 2.11 shows a cross section of a chamber as used in M2-M5 where the detectors consist of four gas gaps.

2.3.4 Logical layout

As mentioned above the different stations and regions of the muon system provide different granularities which are listed in Table 2.3. For example the (x,y)-granularity of M2 goes from 0.63 cm × 3.1 cm in region 1 to 5 cm × 25 cm in region 4 and the particle flux in these regions varies from 37 kHz/cm² to 1 kHz/cm². The segmentations have been chosen
Table 2.2: Readout methods used in the different regions of the muon system.

<table>
<thead>
<tr>
<th>Readout type</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWPC</td>
<td>R4</td>
</tr>
<tr>
<td>Wire pads</td>
<td></td>
</tr>
<tr>
<td>Mixed wire-cathode</td>
<td>R1, R2 in M2, M3</td>
</tr>
<tr>
<td>pads</td>
<td>everywhere else</td>
</tr>
<tr>
<td>Cathode pads</td>
<td></td>
</tr>
<tr>
<td>GEM</td>
<td>R1 in M1</td>
</tr>
<tr>
<td>Anode pads</td>
<td></td>
</tr>
</tbody>
</table>

in that way to satisfy the requirements of rate capability on the one hand and to achieve the required spatial resolution on the other hand. The detector granularity shown in Fig. 2.10 and summarized in Table 2.3 is the granularity as it is seen by the trigger and is called logical layout. The x dimensions of the logical units are mainly determined by the need of a $p_T$ resolution of about 20% for the L0 trigger while the given y dimensions are required to reject background triggers which don’t point to the interaction region.

To form the logical layout all the chambers of the muon system are segmented into physical pads which are grouped together in different ways to obtain the required granularity. In most regions the size of the physical pads is determined by the fact that the electrical capacitance and the rate of a given pad must be limited in order to keep the noise and the dead time of the front-end electronics channels to an acceptable level. For the MWPCs anode wire pads or cathode pads are used to define the physical pads, the GEM chambers in region 1 of station M1 are divided into anode pads. For example for R4 regions where the rate and the required resolution is very moderate a physical pad (wire pad) is obtained just by grouping together a group of adjacent wires. For the inner regions of stations M2 and M3 a mixed read out of wire and cathode pads has been implemented. In this case a logical pad is formed by the crossing of vertical wire pads and cathode pads. The different readout types are summarized in Table 2.2. Each physical pad is read out by one front-end (FE) electronics channel. The FE boards are installed directly on the chambers.

In total the LHCb muon system comprises 122112 physical channels which are OR-ed to 25920 logical channels. The Level-0 trigger provides the 55296 logical pads which are also used for offline muon reconstruction.
Table 2.3: Basic numbers for the five muon station M1-M5 and the four region R1-R4. The first row gives the size of the logical pads in cm² for each region. The segmentations scale in the ratio 1:2:4:8. The second row gives the calculated particle rates for the different regions at nominal luminosity of $L = 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$. The maximal rate which is given in the third row is defined by applying a safety factor to the nominal background rates. These safety factors were applied because of uncertainties in the background calculations and were chosen to be 2 for M1 and 5 for M2-M5. The table shows the correlation between the logical pad size and the particle rate.

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>1 × 2.5</td>
<td>0.63 × 3.1</td>
<td>0.67 × 3.4</td>
<td>2.9 × 3.6</td>
<td>3.1 × 3.9</td>
</tr>
<tr>
<td></td>
<td>230 kHz/cm²</td>
<td>7.5 kHz/cm²</td>
<td>2 kHz/cm²</td>
<td>1.3 kHz/cm²</td>
<td>880 Hz/cm²</td>
</tr>
<tr>
<td></td>
<td>460 kHz/cm²</td>
<td>37.5 kHz/cm²</td>
<td>10 kHz/cm²</td>
<td>6.5 kHz/cm²</td>
<td>4.4 kHz/cm²</td>
</tr>
<tr>
<td>R2</td>
<td>2 × 5</td>
<td>1.25 × 6.3</td>
<td>1.35 × 6.8</td>
<td>5.8 × 7.3</td>
<td>6.2 × 7.7</td>
</tr>
<tr>
<td></td>
<td>93 kHz/cm²</td>
<td>5.3 kHz/cm²</td>
<td>650 Hz/cm²</td>
<td>430 Hz/cm²</td>
<td>350 Hz/cm²</td>
</tr>
<tr>
<td></td>
<td>186 kHz/cm²</td>
<td>26.5 kHz/cm²</td>
<td>3.3 kHz/cm²</td>
<td>2.2 kHz/cm²</td>
<td>1.8 kHz/cm²</td>
</tr>
<tr>
<td>R3</td>
<td>4 × 10</td>
<td>2.5 × 12.5</td>
<td>2.7 × 13.5</td>
<td>11.6 × 14.5</td>
<td>12.4 × 15.5</td>
</tr>
<tr>
<td></td>
<td>40 kHz/cm²</td>
<td>1.3 kHz/cm²</td>
<td>200 Hz/cm²</td>
<td>150 Hz/cm²</td>
<td>130 Hz/cm²</td>
</tr>
<tr>
<td></td>
<td>80 kHz/cm²</td>
<td>6.5 kHz/cm²</td>
<td>1.0 kHz/cm²</td>
<td>750 Hz/cm²</td>
<td>650 Hz/cm²</td>
</tr>
<tr>
<td>R4</td>
<td>8 × 20</td>
<td>5 × 25</td>
<td>5.4 × 27</td>
<td>23.1 × 29</td>
<td>24.8 × 30.8</td>
</tr>
<tr>
<td></td>
<td>12.5 kHz/cm²</td>
<td>230 Hz/cm²</td>
<td>83 Hz/cm²</td>
<td>50 Hz/cm²</td>
<td>45 Hz/cm²</td>
</tr>
<tr>
<td></td>
<td>25 kHz/cm²</td>
<td>1.2 kHz/cm²</td>
<td>415 Hz/cm²</td>
<td>250 Hz/cm²</td>
<td>225 Hz/cm²</td>
</tr>
</tbody>
</table>

2.3.5 Level-0 muon trigger

The Level-0 (L0) muon trigger [7] looks for muons with high transverse momenta because the heavy flavour content of the initial state is indicated by a high $p_T$. About 20% of the total L0 trigger rate are provided by the L0 muon trigger. A muon trigger in the LHCb muon system requires a hit in all five muon stations within a 25 ns time window.

The track finding by the muon trigger starts in station M3. For each hit in a logical pad of M3 a straight line pointing to the interaction region is extrapolated to the other four muon stations. In these stations a field of interest (FOI) is defined as an area around the extrapolation point. If there is at least one hit in the FOI of M1, M2, M4 and M5 the muon track is flagged and the transverse momentum is evaluated by using the track hits in M1 and M2. If the transverse momentum is above a defined threshold (typically $p_T > 1$ GeV/c) the event is selected by the L0 trigger and passed to higher decision levels. In order to apply the described scheme, a hit in all five muon stations is required and a
particle must have a momentum of at least 6 GeV/c.

2.3.6 Electronics

The electronics of the muon system [6] must prepare the information needed by the L0 muon trigger on the one hand and send the data to the Data Aquisition (DAQ) System on the other hand. The whole electronics chain is shown schematically in Fig. 2.12 and can be divided into four steps:

1. The front-end (FE) CARDIAC boards perform the amplification, shaping and discrimination of the 122k chamber signals.

2. The 25920 logical channels are created by logical ORs of the physical channels. This is done on the FE boards and on the Intermediate Boards (IB) if the logical channels are made of physical channels belonging to different chambers.

3. On the Off Detector Electronics (ODE) the data from the logical channels is tagged with the number of the bunch crossing and sent to the L0 trigger via optical links.

4. A fine time measurement is performed on the ODE boards and the data is sent to the TELL1 board and then to the DAQ system.

Front-end electronics

The front-end (FE) electronics of the muon system [6] are directly mounted on the muon chambers in form of FE boards called CARDIAC boards which are plugged onto the chambers. Each CARDIAC is powered by 2.5 V and consists of two CARIOCA chips and one DIALOG chip [9, 10]. The number of CARDIAC boards on the chamber differs from chamber type to chamber type. The chambers in region 4 only have 3 boards while for example in region 2 of station M1 the chambers are equipped with 24 CARDIACs. In total there are about 8000 boards installed on the chambers of the muon system. The high particle rates of up to 800 kHz per FE-channel in some detector regions and the high
radiation doses of up to 5000 Gy [6] expected near the beam pipe in 10 years of operation demand the use of very fast and radiation hard front-end chips.

The **CARIOCA chip** [9] consists of eight channels and performs the Amplification, Shaping and Discrimination (ASD chip) of the input signals. Since there are different readout types in the muon system (cathode and wire readout) the chip has been developed in two versions to handle both, the positive and negative signals. The CARIOCA has individual thresholds for the eight channels which allows to take into account the non-uniformity of separate channels and therefore to set optimal thresholds. The equivalent noise is about 2000 electrons at 0 capacitance and increases with $42 - 45 \text{ e/pF}$ (section 4.1).

Fig. 2.13 shows the block diagram of one CARIOCA channel. The first stage consists of two current amplifiers. One amplifier is connected to the chamber pad and the other one (dummy amplifier) provides DC balance to the shaper and reduces pickup, crosstalk and noise. The amplifier must cope with the large difference in detector capacitance in the muon system which ranges from 51 pF for the chambers in M1R3 to 245 pF for the
M5R4 chambers. The amplifier is designed to handle positive and negative signals. In the indicated capacitance range the gain of the positive (negative) amplifier decreases from about $3.2 \text{ mV/FC} (2.8 \text{ mV/FC})$ to $2.1 \text{ mV/FC} (1.6 \text{ mV/FC})$ and the peaking time increases from $7 \text{ ns} (7 \text{ ns})$ to $14 \text{ ns} (15 \text{ ns})$. The following shaper is a one stage pole/zero filter with 2 poles and 2 zeros. The signal has to be shaped to a narrow pulse in order to handle the high rates expected in the muon system. The gain of the shaper is about $4.0 \text{ mV/FC}$ and $3.6 \text{ mV/fC}$ for the positive and negative polarity amplifiers. The shaper contributes to the peaking time with approximately $1 \text{ ns}$. A tail cancellation network is implemented which is needed to remove the long $1/(t + 1.5 \text{ ns})$ signal tail. The next stage is a differential amplifier which provides further shaping and a gain of about $6.3 \text{ mV/FC} (7.4 \text{ mV/FC})$ for the positive (negative) input polarity. In addition a baseline restoration (BLR) circuit consisting of three amplifiers is implemented to correct for baseline fluctuations. The following discriminator is a differential one. The discriminator output is sent to the LVDS driver which provides the output signal of the CARIOCA chip. Putting the whole chain together the gain (sensitivity) is about $12.5 \text{ mV/FC}$ for the positive and about $13 \text{ mV/FC}$ for the negative chip.

For the Triple-GEM chambers in region 1 of station M1 a special version of CARIOCA, CARIOCA-GEM [9], is used. Because of the lower gas gain of the GEM chambers the thresholds are lower and the shaping time is longer. A tail cancellation is not needed because of the pure electron signal of the GEM chambers.
The **DIALOG chip** [10] has 16 input and 8 output channels. It combines the signals of two CARIOCA chips and performs the logical OR of two corresponding CARIOCA channels in order to reduce the number of channels as described in section 2.3.4. Furthermore it handles the thresholds and time alignment of the CARIOCA channels. The DIALOG chip uses 8-bit DACs (Digital to Analog Converters) to provide 18 separate threshold signals for the discriminators. The threshold voltage ranges from 625 to 1200 mV and can be set in steps of 2.35 mV (register unit [r.u.] or rDAC). The chip allows to time align the individual channels by providing the possibility to delay the channels in steps of 1.6 ns. In addition the DIALOG chip is equipped with 16 counters that allow to determine the number of threshold crossings per channel. The chip also offers features to debug and monitor the system and allows to mask individual channels.
Chapter 3

Simulation of the timing properties of the LHCb muon chambers

The LHC bunch crossing rate of 40 MHz and the intense flux of particles in the muon system impose challenging requirements on the efficiency, time resolution, rate capability and ageing characteristics of the MWPCs used in the LHCb muon system, and also on the speed and radiation resistance of the electronics. To fulfill these requirements it is necessary to have a deep understanding of the detector and of the effects that limit the performance.

There has been done a lot of work in the past [11, 12, 13] which concentrated on the optimization of the main MWPC parameters like wire spacing, wire diameter, gap size, gas mixture and electronics characteristics of the muon chambers while keeping in mind the physics requirements and the technical constraints. Based on these studies the final MWPC geometry with a wire spacing of 2 mm, a gap of 5 mm and a wire diameter of 30 µm was chosen.

The work described in this chapter takes up these studies but now concentrates on the simulation of the muon chambers with the final geometry and on the performance limiting effects. It is of particular interest to understand the influence of electronics noise and the dependence of the time resolution and efficiency on the threshold, since this will help to optimize the threshold settings of the muon system which will be discussed in chapter 4.
Figure 3.1: The plot shows the effect of the CF$_4$ content on the time resolution and efficiency. The gas mixture which is currently used in the LHCb muon system is Ar/CO$_2$/CF$_4$ 40/55/5, for the simulations a CF$_4$ amount of 10% was adapted because more test beam data have been available for this mixture. The influence of the CF$_4$ content is rather small at least for a 5% variation of CF$_4$.

A detailed simulation study of the MWPCs of the LHCb muon system has been performed using the drift chamber simulation program GARFIELD [1]. The simulations are done for the final MWPC geometry as stated above. The simulations are compared with measurements to ensure that the simulation reproduces the measurement well. Since nearly all test beam measurements were done with the gas mixture Ar/CO$_2$/CF$_4$ 40/50/10 this mixture has also been used in the simulations. However, ageing tests have shown that even a 10% concentration of CF$_4$ in the gas mixture leads to etching effects in the chambers [14]. Therefore it was decided to reduce the CF$_4$ content to a maximum of 10%. The effect of the CF$_4$ concentration on the chamber performance is anyway rather small. Fig. 3.1 is taken from [15] and shows the influence of the CF$_4$ amount on the time resolution and efficiency.

The good agreement between measurement and simulation (section 3.2) allows to study the time resolution limiting parameters such as ionization fluctuations, cluster position fluctuations, diffusion, electronics noise, track position and wire spacing in detail to show
how they contribute to the time resolution. The simulation is pushed further to point out the limit of time resolution for the MWPCs of the LHCb muon system and to show how this limit could be reached.

3.1 Detector physics simulation

3.1.1 GARFIELD - simulation of gaseous detectors

GARFIELD [1] is a Fortran-based computer program for the detailed simulation of gaseous detectors, in particular for the simulation of two- and three-dimensional drift chambers. It can calculate field maps, electron and ion drift lines, drift time tables and arrival time distributions, signals induced on electrodes by moving charged particles, etc. The GARFIELD package version 9 provides an interface to the MAGBOLTZ program [16] and to the HEED program [17]. MAGBOLTZ calculates the transport properties such as drift velocity, transverse and longitudinal diffusion, amplification and attachment of electrons under the influence of electric and magnetic fields in nearly arbitrary gas mixtures by solving the Boltzmann transport equations. The HEED program calculates the energy deposit of fast particles in gases based on the Photo-Absorption Ionization (PAI) model [18] which uses the atomic photo absorption cross sections. For the computation HEED also takes into account delta electrons and multiple scattering of the incoming particles.

The GARFIELD input code itself is divided into several sections:

- the MAIN section: top level input, variable declaration
- the CELL section: the chamber layout is entered
- the GAS section: interfaces to MAGBOLTZ and HEED, transport and ionization properties are computed
- the FIELD section: visualisation of the field
- the DRIFT section: drifting of electrons and ions
3.1.2 Geometry, fields, potentials and capacitance

The Multi Wire Proportional Chambers (MWPCs) used in the LHCb muon system have the typical geometry shown in Fig. 3.2. The wires are separated by 2 mm and are placed symmetrically in a 5 mm gas gap. The cathode plates are grounded while the anode wires are at a voltage of typically 2.65 kV during operation. This layout defines the CELL in our program.

In the following the field and potential in the chamber will be evaluated. In the simulation this is all done by GARFIELD. For the calculations in this section it is assumed that the cathode plates extend mathematically to infinity and that the anodes consist of an infinite row of wires with a wire spacing of \( s = 2 \) mm. Furthermore one can say that \( \cosh \frac{2h}{s} \gg 1 \) and therefore one can apply the Weber approximation [19] which simplifies the analysis.

One can show that if the anodes are at potential \( V_a \) and the cathodes at ground potential the potential function is given by

\[
V(x, y) = V_a \left\{ 1 - C \ln \frac{2 (\cosh 2\pi y/s - \cos 2\pi x/s)}{(2\pi r_a/s)^2} \right\} \tag{3.1}
\]

\[\text{Figure 3.2: MWPC geometry.}\]
where
\[ C = \frac{1}{\ln\left(\frac{r_c}{r_a}\right)^2}. \] (3.2)

The effective cathode radius is defined by
\[ r_c = \frac{s}{2\pi} e^{\frac{\pi h}{s}}. \] (3.3)

With a wire spacing of \( s = 2 \text{ mm} \) and an anode-cathode spacing of \( h = 2.5 \text{ mm} \) we get \( r_c = 1.62 \text{ cm} \).

Using Eq. 3.2 one can define the capacitance per unit length of wire as
\[ C_u = 4\pi\epsilon_0 C \] (3.4)

From Eq. 3.1 one can evaluate the potential very close to the wire \((x, y << s)\) and the potential for regions far away from the wires \((\cosh 2\pi y/s >> 1)\). For the first case one gets
\[ V(r) = V_a \left\{ 1 - C \ln \left( \frac{r}{r_a} \right)^2 \right\} \] (3.5)

with \( r = (x^2 + y^2)^{1/2} \). As expected the potential in the vicinity of the wire is the same as for a coaxial geometry [20]. The field near the wire surface is given by
\[ E_r = \frac{2CV_a}{r}. \] (3.6)

For regions near the cathodes we obtain
\[ V(y) = V_a \left\{ \frac{2\pi C}{s} (h - |y|) \right\} \] (3.7)

and
\[ E_y = \pm \frac{2\pi CV_a}{s}. \] (3.8)

The potential falls uniformly with \(|y|\).

By using the above formulas one can evaluate the fields for different chamber geometries and wire diameters [11]. Fig. 3.3 is taken from [12] and shows the electric field in the chamber.
3.1.3 Gas ionization

If a charged particle, for example a muon, traverses a MWPC of the muon system it leaves a track of ionization along its trajectory since it interacts with the gas in the chamber. The number of interactions with gas atoms per unit of track length is Poisson distributed since the encounters are independent. Therefore the distances between the interactions are exponentially distributed.

There are different ways a charged particle can ionize the detector gas [18]:

- The fast particle interacts with a gas atom by transferring energy and one or more electrons are ejected from the atom instantaneously. This is called primary ionization.

- Another possible way to produce electron-ion pairs is secondary ionization where
Figure 3.4: The left plot shows the average number of clusters produced by a traversing muon per cm of gas as a function of the muon energy. The figure on the right shows the electron drift velocity as a function of the electric field. In the chambers of the muon system the field is higher than 6 keV/cm. The influence of the CF₄ content is rather small.

Free charge carriers are produced either in collisions of primary ionization electrons with atoms, or via excitation of atoms by the traversing particles. In the first case the atoms can eject again one or more electrons instantaneously while in the latter case the excited atom can return to its ground state by different mechanisms. Most probably it will release the excitation energy by emitting an Auger electron or a photon.

Since the secondary ionization normally happens very close to the primary interaction localized clusters of electrons and ions will remain along the particle track. Fig. 3.4 shows the average number of clusters for different gases as a function of the muon energy and was taken from [12]. The energy dependence is given by the Bethe-Bloch equation [18] which describes the energy loss on a track.

\[
\frac{dE}{dx} = \frac{4 \pi Ne^4}{mc^2} \frac{1}{\beta^2 z^2} \left\{ \ln \frac{\sqrt{2mc^2E_{max}}\beta\gamma}{I} - \frac{\beta^2}{2} - \frac{\delta(\beta)}{2} \right\}
\]  

(3.9)
In the formula $N$ is the number density of electrons in the gas, $e$ is the elementary charge, $mc^2$ gives the rest energy of the electron, $z$ is the charge of the particle traversing, $\beta$ the velocity of the particle in terms of the velocity of light $c$ and $\gamma$ is the Lorentz factor. $I$ describes the mean excitation energy of the atom, $E_{\text{max}}$ is the maximum transferable energy in a single collision and $\delta$ is a correction factor which takes into account the density effect \[18\].

A muon in LHCb must have at least 6 GeV in order to traverse all five stations of the muon system which means that for the gas Ar/CO$_2$/CF$_4$ 40/50/10 we can expect approximately 42 clusters/cm (Fig. 3.4) with an average number of 2.35 electrons/cluster \[11\]. So one can expect to have about 100 electrons in a double gap. For the gas mixture Ar/CO$_2$/CF$_4$ 40/55/5 one can expect about 39 clusters/cm and an average number of 2.5 electrons per cluster \[21\]. So on average one will have approximately 97 electrons in a double gap. As already mentioned in the introduction there’s only a minor difference between the two gas mixtures.

In the simulation HEED is taking care of the gas ionization process. It calculates the energy deposit in the chamber using the Photo-Absorption Ionization (PAI) model which is based on measured photo absorption cross sections.

### 3.1.4 Drift and diffusion

The electrons and ions which are produced in the ionization process quickly lose their energy by multiple collisions with the gas atoms and molecules. Their direction of motion in the gas is completely randomized in each collision. The locally produced clouds of electrons and ions diffuse according to a Gaussian distribution \[20\].

\[
\frac{dN}{N} = \frac{1}{\sqrt{4\pi D t}} \exp\left(-\frac{x^2}{4Dt}\right) dx
\]

where $dN/N$ is the fraction of the charge in the length element $dx$ at distance $x$. $D$ is the diffusion coefficient.
Since the charge carriers in the chamber are exposed to an electric field their motion will be a superposition of the statistically disordered diffusion and an ordered drift according to the electric field. The drift velocity can be written as

$$
\vec{v}_{\text{drift}} = \mu(E) \vec{E}
$$

where $\mu(E)$ is the charge carrier mobility.

In the simulation the transport properties of electrons are handled by MAGBOLTZ. It calculates the drift velocity, transverse and longitudinal diffusion, etc. by solving the Boltzmann transport equations. Fig. 3.4 shows the electron drift velocity as calculated with MAGBOLTZ for three different gas mixtures as a function of the electric field. The influence of the CF$_4$ content is small.

The ions travel at a velocity which is approximately three orders of magnitude smaller than the one of the electrons. At low fields the ion mobility is constant while at high fields it starts to become field dependent and $\propto 1/\sqrt{E}$. For example for Ar$^+$ ions in Ar the field dependence starts to play a role at approximately 75 kV/cm [22]. In the simulation the ion mobility has to be entered in form of a separate input file (ion mobility file). For the detector simulation we assumed a constant ion mobility averaged over the chamber volume. The ion mobility was set to 1.4 cm$^2$/Vs. Although the field on the wire surface is quite high (≈ 250 kV/cm) and the field dependence of the ion mobility becomes important, a constant mobility is a good approximation for the whole chamber volume.

3.1.5 The avalanche process

The electrons which are produced in the ionization process will drift towards the wire according to the electric field present in the chamber. As the electrons approach the wire surface they travel in an increasing electric field which is given by

$$
E_r = \frac{\lambda}{2\pi \epsilon_0 r} \frac{1}{r}
$$

where $\lambda$ is the linear charge density on the wire. If the electric field gets strong enough an avalanche process starts because the electrons can gain sufficient energy between collisions
with the gas molecules to ionize the gas and create other electrons and ions. The avalanche process comes to an end when all the electrons are collected on the wire. The mean free path of the electrons at normal gas density is of the order of some $\mu$m. So in order to start an avalanche the electric field has to be of the order of some $10^4$ kV/cm and the wire diameter has to be of the order of a few $10$ $\mu$m [18]. The MWPCs used in the LHCb muon system fulfill both criteria [11, 12].

The amplification process is described by the first Townsend coefficient $\alpha$ and the increase of the number of electrons over a given path length $ds$ can be written as

$$dN = N\alpha ds.$$ \hfill (3.13)

The first Townsend coefficient $\alpha$ depends on the excitation and ionization cross sections of the accelerated electrons and therefore also on the electric field. By using this coefficient the gas amplification factor, also called gas gain, can be determined by

$$G = \frac{N}{N_0} = \exp \left[ \int_{s_{min}}^{r_a} \alpha(s) ds \right] = \exp \left[ \int_{E_{min}}^{E(r_a)} \frac{\alpha(E)}{dE/ds} dE \right]$$ \hfill (3.14)

where $s_{min}$ is the distance from the wire where the field is just enough to start the avalanche process, $r_a$ is the wire radius and $N$ and $N_0$ are the final and initial number of electrons. By assuming that the first Townsend coefficient is proportional to the field $[23]$, $\alpha = \beta E$, the so called Diethorn formula can be found.

$$\ln G(V) = \frac{\ln 2}{\ln \left( \frac{r_e}{r_a} \right)} \frac{V}{\Delta V} \ln \left( \frac{r_e}{r_a} \right) E_{min}(\rho_0) \left( \frac{\rho}{\rho_0} \right)$$ \hfill (3.15)

In the formula $\Delta V$ is the average potential which is needed to produce one electron in the avalanche, $\rho$ and $\rho_0$ are the gas and the normal gas density. The Diethorn parameters can be found by using a measured gas gain curve [11]. For the gas Ar/CO$_2$/CF$_4$ 40/50/10 and for a 30 $\mu$m wire one finds

$$E_{min} = 46.501 \text{ kV/cm}$$
$$\Delta V = 42.027 \text{ V}$$
By determining these parameters one can estimate the operating voltages for different chamber geometries and wire diameters. The gain of the MWPCs of the LHCb muon system with a wire diameter of 30 $\mu$m and an operating voltage of 2.65 kV is approximately $10^5$.

In principle MAGBOLTZ is able to calculate the Townsend coefficient $\alpha$, so one can derive the gas gain for a given voltage by integrating this coefficient. But since the avalanche multiplication is an exponential process, small errors in the Townsend coefficient will result in large uncertainties in the gas gain. For this reason the gas gain is taken from measurements [24] and is entered in the simulation as a fixed input parameter. The gain was determined to $10^5$ at 2.65 kV and doubles every 106 V. However, these results are only known with an accuracy of 20 $-$ 30 %. Therefore the gas gain in the simulation had to be scaled with a factor of 1.2.

The calculation of the energy loss in the gas done by HEED and the evaluation of the transport properties done by MAGBOLTZ form the GAS section of the simulation. The drift of the electrons towards the wires is performed in the DRIFT section. Fig. 3.5 shows a simulated track of a muon with 3.6 GeV. The drift lines of the electrons are indicated and show the influence of diffusion. Some electrons don’t reach the wire because of attachment.

### 3.1.6 Signals

The electrons and ions produced in the avalanche process will be accelerated towards the wires and cathodes respectively. Since the avalanche develops very close to the wire surface and since the electrons move very fast they will reach the wire within a time of a few ns. On the other hand the much heavier ions typically need several $10^2$ $\mu$s to arrive at the cathodes. The movement of the electrons and ions in the chamber induces an electric current on the electrodes.

To determine the arrival times and the induced current signals we make some simplifica-
tions. In a first step we can assume that the electrons are created directly at the wire surface and therefore don’t move at all. Although we have high fields near the wire we can assume a constant ion mobility since for the whole gap an average constant value is a satisfying approximation. Since the field near the wire surface and the drift velocity are given by Eq. 3.6 and Eq. 3.11 a single ion is moving according to

\[ r(t) = r_a \sqrt{1 + \frac{1}{t_0}} \]  

(3.16)

where

\[ t_0 = \frac{r_a^2 \ln \frac{r_c}{r_a}}{2V_a \mu} \].

(3.17)

The maximum travel time is given by

\[ t_{max} = t_0 \left[ \left( \frac{r_c}{r_a} \right)^2 - 1 \right] \].

(3.18)

The ion is exposed to an electric field given by

\[ E(t) = \frac{V_a}{r_a \ln \frac{r_c}{r_a}} \frac{1}{\sqrt{1 + \frac{t}{t_0}}} = \frac{E_a}{\sqrt{1 + \frac{t}{t_0}}} \].

(3.19)

According to Ramo’s theorem [25] the movement of the ion induces a current

\[ i(t) = -\frac{q}{V} r(t) E[r(t)] = \frac{q}{2 \ln \frac{r_c}{r_a}} \frac{1}{t + t_0} \].

(3.20)

With a wire voltage of \( V_a = 2650 \text{ V} \), a wire radius \( r_a = 15 \mu \text{m} \), an equivalent cathode radius \( r_c = 1.62 \text{ cm} \), \( q = e_0 = 1.609 \times 10^{-19} \text{ C} \) and a constant ion mobility \( \mu = 1.4 \text{ cm}^2/\text{Vs} \) we get:

\[ t_0 = 2.12 \text{ ns} \]
\[ t_{max} = 2.46 \text{ ms} \]
\[ i(t = 0) = 5.44 \text{ pA} \]

A 6 GeV muon produces on average 100 electrons in 1 cm of the gas Ar/CO\(_2\)/CF\(_4\) 40/50/10. Since the gas gain is \( \approx 10^5 \) at 2650 V this muon induces a current pulse with a peak of 54.4 \( \mu \text{A} \).
**Figure 3.5:** The left plot shows a simulated track of a 3.6 GeV muon through the chamber. The electron drift lines are indicated. The crosses indicate that some electrons don’t reach the wire due to attachment. The figure on the right shows the corresponding induced signal on a group of wires. The peaks correspond to the individual electrons which arrive at the wire.

These are of course only approximated results and the induced signal will have a more complex form in reality. However, since the preamplifier integration time is only 10 ns while the delta pulse of the electron is much shorter and since the field dependence of the ion mobility starts to affect the signal only at times comparable to the peaking time we can use this approximation.

In the SIGNAL section of the simulation GARFIELD calculates the signals induced on the electrodes. Fig. 3.5 shows the signal induced on the wires by a 3.6 GeV muon. The peak of the current signal is smaller than evaluated before because the event was chosen randomly out of a sample of 2000 simulated events and the amount of charge deposited in the chamber fluctuates from event to event.
Figure 3.6: The left plot shows the measured FE electronics output shapes for a $\delta$ input pulse of 90 fC for different detector capacitances. The figure on the right shows the normalized output signal.

3.1.7 Electronics

The front-end electronics (FE) of the muon chambers are characterized by their delta response $f(t)$ [11].

$$f(t) = n^{-n}e^{nt} \left(\frac{nt}{t_p}\right)^n e^{-\frac{nt}{t_p}}$$  \hspace{1cm} (3.21)

In the equation $t_p$ is the amplifier peaking time and $n$ is the number of integration stages. In order to simulate the electronics response we used measured delta responses which are shown in Fig. 3.6 for the negative preamplifier for different detector capacitances. The electronics output signal is given by convoluting the induced signal with the electronics delta response $f(t)$.

$$g(t) = \int_0^t f(t-t')i(t')dt'$$  \hspace{1cm} (3.22)

To simulate electronics noise a Gaussian noise signal with defined $\sigma_{\text{noise}}$ was added to the induced current signal. Fig. 3.7 shows a simulated random noise signal. After adding noise the signal is convoluted with the normalized electronics delta response and finally the threshold crossing time is found (Fig. 3.7). This is the final stage in the SIGNAL section and also in the whole simulation chain.
Figure 3.7: On the left one can see a simulated noise signal. The plot on the right shows the induced signal of a muon on a group of wires after adding noise and a convolution with the electronics delta response.

3.2 Comparison simulation - measurement

To check the quality of the simulation, a detailed comparison with measurements was made. A single event was simulated in the following way: a particle which is defined by it’s type, charge, energy and track coordinates is sent through the chamber. HEED calculates the ionization along the track based on the atomic photo absorption cross sections of the specified gas. Then GARFIELD tracks the charges in the electric field according to the transport properties (diffusion, drift velocity) calculated by MAGBOLTZ for the specified gas mixture. Each electron arriving at the wire is multiplied by a specified gas gain number. The ions produced in the avalanche process are tracked to the electrodes and the induced current signal is calculated. In a next step electronics noise is added to the signal. Then the signal is convoluted with the electronics delta response of the amplifier and shaper circuit and finally the threshold crossing time of the signal is found.

The output was analysed in the same way as the real data which have been taken from measurements performed at the T11 test beam at the Proton Synchrotron (PS) at CERN
Table 3.1: Operating parameters used at the T11 test beam measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>3.6 GeV pions</td>
</tr>
<tr>
<td>Chamber type</td>
<td>M3R1 chamber</td>
</tr>
<tr>
<td>Detector capacitance</td>
<td>80 pF</td>
</tr>
<tr>
<td>Detector sensitivity</td>
<td>11 mV/FC</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>2.65 kV</td>
</tr>
<tr>
<td>Gas mixture</td>
<td>Ar/CO₂/CF₄ 40/50/10</td>
</tr>
<tr>
<td>Threshold ($5\sigma_{\text{noise}}$)</td>
<td>45 mV ($\approx 4 - 5 \text{ fC}$)</td>
</tr>
</tbody>
</table>

A M3R1 chamber was tested in a 3.6 GeV pion beam. The operating parameters can be found in Table 3.1. The two double gaps and four single gaps of the 4-gap chamber have been analysed separately. Fig. 3.8, Fig. 3.9, Fig. 3.10 and Fig. 3.11 show a comparison of the measurements with the simulation for the different gaps.

One can see that there is a very good agreement with the measurements. The slightly different efficiencies of single gap S1 and S2 (Fig. 3.8) can be explained by the fact that the gas gain can vary up to 20% for different gaps of the same chamber. The simulated time resolution agrees well with the measured one and also the simulated time walk, which is due to the fact that different voltages result in different pulse heights and therefore in different threshold crossing times, is in good agreement with the measurement.

Fig. 3.11 shows the efficiency for an infinite time window (hit efficiency) as a function of the threshold which is given as a fraction of the median signal. Knowing from the measurement that at 2.145 kV the hit efficiency is 50% and that the gas gain doubles every 106 V one can convert voltage into threshold fraction. One can see from the figure that with a threshold of up to 30% of the median signal one can expect an efficiency of 99%. However, in order to achieve a double gap efficiency of 99% within a 20 ns time window one should set the threshold to 10% of the median signal. This is important to retain full system redundancy. This will be discussed in more detail in chapter 4.

The good agreement between simulation and measurement shows that we really understand our detector and the individual processes and allows us to perform further simulations on our detector and to study the time resolution limiting contributions in detail.
Figure 3.8: The plots show a comparison between the simulated and measured efficiency as a function of high voltage for the two double gaps (S1S2 and S3S4) and the four single gaps (S1, S2, S3 and S4) of the tested 4-gap chamber. The efficiencies were evaluated for a 20 ns time window and an infinite time window. The solid markers indicate the measurement, the open markers show the simulation.

Figure 3.9: The plots show a comparison between the simulated and measured time resolution for the two double gaps and the four single gaps of the tested 4-gap chamber. The solid markers indicate the measurement, the open markers show the simulation.
Figure 3.10: The plots show a comparison between the simulated and measured time walk for the two double gaps and the four single gaps of the tested 4-gap chamber. The solid markers indicate the measurement, the open markers show the simulation. Different voltages result in different pulse heights and therefore in different threshold crossing times (Fig. 3.17).

Figure 3.11: The plot on the right shows a comparison between the simulated and measured double gap hit efficiency for different voltages as a function of the threshold which is given as a fraction of the median signal. The solid markers indicate the measurement, the open markers show the simulation. One can convert voltage into threshold fraction using the equation given in the left plot which also shows the measured efficiency. At 2.145 kV the hit efficiency is 50 %.
3.3 Time resolution limiting parameters

It has been shown that the simulation agrees well with measurements and so the contributions of individual effects which limit time resolution can be studied in detail by just switching them on or off in the simulation. In the next sections the influence of detector capacitance, diffusion, electronics noise, ionization fluctuations, cluster position fluctuations, track positions and wire pitch on time resolution will be shown. It is important to mention that during one run of simulation only one contribution is switched off while all the others are still considered in the simulation. Most of the effects are strongly correlated and so it makes no sense to turn off all contributions but one and study the impact of this individual effect on time resolution. Apart from that the conditions are the same as for the T11 measurements. The parameters are summarized above in Table 3.1.

3.3.1 Detector capacitance

The detector capacitance of the MWPCs in the LHCb muon system varies from 50 pF for the M1R3 chambers to 245 pF for the M5R4 chambers and the detector sensitivity decreases by about a factor 2 in this range [26]. The Equivalent Noise Charge (ENC) [11] which characterizes the front-end electronics is defined as the signal charge which results in a signal to noise ratio of unity. Because of the large spread in detector capacitance and noise rate which is due to the granularity of the muon system, the ENC varies from approximately 0.5 fC to 2 fC.

Fig. 3.12 and Fig. 3.13 show a simulation of the efficiency, time resolution and time walk as a function of high voltage for different detector capacitances. The threshold was set to $5 \times $ ENC in order to have a threshold well above the noise level. The values are given in Table 3.2. Since the ENC is depending on the detector capacitance, i.e. the pad size, one can decrease the threshold at low capacitances and improve time resolution and efficiency.
Table 3.2: Parameters used for simulating the influence of detector capacitance on efficiency, time resolution and time walk. Since the ENC is depending on the detector capacitance one can decrease the threshold at lower capacitances. The threshold in fC can be calculated by using the sensitivity.

<table>
<thead>
<tr>
<th>Capacitance [pF]</th>
<th>Threshold (5 × ENC) [mV]</th>
<th>Sensitivity [mV/fC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>56</td>
<td>40</td>
<td>12</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>150</td>
<td>56</td>
<td>8.5</td>
</tr>
<tr>
<td>220</td>
<td>61</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 3.12: The plots show the dependence of the double and single gap efficiency in a 20 ns time window on the detector capacitance as a function of high voltage.
Figure 3.13: The plots show the dependence of the double gap time resolution and time walk on the detector capacitance as a function of high voltage.

Figure 3.14: The figure shows the geometry of a double gap with wire staggering. The wires in the second gap are shifted by half a wire pitch.

3.3.2 Diffusion

As explained in section 3.1.4 the ions and electrons produced in the ionization process will lose their energy by multiple scattering with the gas molecules. A locally produced ionization diffuses corresponding to a Gaussian distribution. As the charge carriers are exposed to an electric field, a drift along the electric field lines will be superimposed over the statistically disordered diffusion. One can distinguish between longitudinal diffusion in the direction of the field and transversal diffusion perpendicular to the electric field.
The effect of diffusion on time resolution is shown in Fig. 3.15. One can see that diffusion has only a very small influence on double gap resolution. The effect of diffusion is almost completely suppressed by the staggered geometry of the double gap where the wires in the second gap are shifted by half a wire pitch (Fig. 3.14).

In case of a single gap, diffusion even improves the time resolution. This is in contrast to drift chambers where diffusion will always decrease the position resolution [27]. The diffusion has a bigger influence on electrons that are created far away from the wire since their drift time is long compared to electrons produced in the vicinity of the wire and so the arrival time distribution of late electrons is wider than the distribution of the early ones. In addition, the mean arrival time of the early electrons is shifted on average to a higher value under the influence of diffusion because only a few electrons will arrive faster than before, since obviously the electrons cannot arrive at the wire before their creation. As an effect, the arrival time deviation of all electrons becomes smaller and the time resolution improves.
Figure 3.16: The plot shows the effect of charge and cluster position fluctuations on time resolution. The open dots indicate the resolution obtained if the primary ionisation is calculated by HEED, the solid squares show the results assuming 2 electrons per cluster and an exponential cluster spacing and the solid triangles indicate the resolution using a fixed number of electrons per cluster and a cluster spacing of 200 µm.

3.3.3 Charge and cluster position fluctuations

To study the impact of charge and cluster position fluctuations on time resolution we assume a fixed number of electrons per cluster and choose an equal or exponential cluster spacing, respectively. The results are shown in Fig. 3.16. The open dots indicate the resolution obtained if the primary ionisation is calculated by HEED, the solid squares show the results assuming 2 electrons per cluster and an exponential cluster spacing and the solid triangles indicate the resolution using a fixed number of electrons per cluster and a cluster spacing of 200 µm.

As one can see from Fig. 3.16, charge fluctuations have a large impact on time resolution because different charges result in different pulse heights and therefore in different threshold crossing times and reduced time resolution. This effect is called time slewing.
The distance between ionization clusters is distributed exponentially since the primary interactions are independent. The influence of cluster position fluctuations is also shown in Fig. 3.16. They have a smaller influence on the time resolution than charge fluctuations. The effect is small because the ionization density is already quite high.

### 3.3.4 Electronics noise

Electronics noise causes additional fluctuations of the threshold crossing times. However, as one can see from Fig. 3.18, this direct impact of electronics noise on time resolution is very small. The signal height is strongly depending on high voltage and so noise starts to play a more important role at low voltage values because the intersection angle between the leading edge of the signal and the threshold becomes smaller (Fig. 3.17).
Figure 3.18: The plots show the effect of electronics noise on the double gap and single gap time resolution. The open circles indicate the resolution if we assume no noise, the solid dots show the time resolution taking into account all effects.

In addition to this small direct impact electronics noise has a big indirect influence on time resolution as it determines the lower limit for the threshold. If the noise were smaller we could decrease the threshold and improve time resolution and efficiency. Fig. 3.22 shows the dependence of the time resolution on the threshold which is given as a fraction of the median signal.

It is important to realize that the effect of electronics noise is strongly correlated with the contribution of charge fluctuations. Electronics noise corrects for the time slewing effect to some extent. For long signal rise times, noise shifts the threshold crossing times on average to smaller values, while for short rise times the shift is on average smaller, since the angle between the leading edge and the threshold is bigger.

3.3.5 Track position

Fig. 3.19 and Fig. 3.20 show the time resolution and the average arrival time as a function of the track position for a single gap and double gap, respectively. As one can see from
Fig. 3.19, the single gap time resolution is mainly dominated by the position of the track. A difference of about 1 mm in track positions translates into an arrival time separation of nearly 16 ns. The time resolution gets better for larger drift distances since a defined separation of two electrons translates into a smaller arrival time difference.

On the other hand the double gap resolution is mainly affected by intrinsic statistical effects. The contribution of the track position is very small for a staggered geometry. As one would expect the time resolution is optimal for tracks in between of two staggered wires since the drift distance is maximal in this case and the spread in arrival times is therefore minimal.

**Figure 3.19:** The left plot shows the mean arrival time as a function of the position of the track in a single gap. A difference of about 1 mm in track positions translates into an arrival time separation of nearly 16 ns. The plot on the right shows the corresponding time resolution. The resolution increases with increasing distances from the wire since the arrival time separation is reduced.
Figure 3.20: The left plot shows the mean arrival time as a function of the position of the track in a double gap. The arrival time separation is only about 1.4 ns, the time resolution is mainly dominated by intrinsic statistical effects. The plot on the right shows the corresponding time resolution.

3.3.6 Wire pitch

The MWPCs of the LHCb muon system were initially planned with a wire spacing of 1.5 mm but finally it was decided to increase the wire pitch to 2 mm. Fig. 3.21 shows the dependence of the time resolution on the wire spacing. Decreasing the wire pitch results in improved time resolution since the drift time is shorter and arrival time fluctuations are reduced. One can see that by decreasing the wire pitch from 2 mm to 1.5 mm one could improve the double gap resolution by $\approx 25\%$. But at the same time one has to increase the high voltage from 2.65 kV to 3.05 kV in order to reach the same gas gain of about $10^5$. Raising the high voltage is not desirable because of potential stability problems and undesired effects on the chamber borders. Other disadvantages of a smaller wire spacing are complications in the chamber construction and increased costs. Because of these reasons and since a time resolution $< 3.5$ ns can be achieved with a wire spacing of 2 mm, it was finally decided to go to 2 mm pitch.

One can see from Fig. 3.21 that the time resolution doesn’t really improve for a wire pitch
Figure 3.21: The plots show the influence of the wire spacing on the time resolution of a double gap and single gap, respectively.

< 1.5 mm which is due to the primary ionization statistics. Since the number of interactions is Poisson distributed the distance between the clusters is distributed exponentially. This doesn’t allow to improve the resolution by decreasing the wire pitch and therefore one reaches a fundamental limit of MWPCs operated at 1 bar. On the other hand, for a bigger wire spacing the time resolution is determined by the track positions.

3.4 Time resolution optimization

In the previous sections we saw that due to the time slewing effect the influence of charge fluctuations is a main contribution to the time resolution of our chambers. So in order to improve the performance of the detector one should aspire to correct for the time slewing effect. There are several possibilities to achieve this goal.

The following simulations were done at 2.65 kV with a gas gain of $10^5$ and the gas mixture Ar/CO$_2$/CF$_4$ 40/50/10. The threshold was 45 mV. With 100 pF an average detector capacitance was chosen. In order to improve the time resolution one could:
Figure 3.22: The left plot shows the dependence of the double gap time resolution on the threshold which is given as a fraction of the median signal. The pulse height distribution in a double gap filled with the gas mixture Ar/CO$_2$/CF$_4$ 40/50/10 operated at 2.65 kV is shown in the right plot. The median pulse height is 1518 mV.

1. Lower the threshold. Using a high threshold has two disadvantages. With a high threshold we trigger on late electrons which have a larger arrival time distribution compared to early ones as explained in section 3.3.2. The second and main disadvantage of using a high threshold is the increased time slewing. This effect is shown in Fig. 3.17. For a higher threshold the threshold crossing time fluctuations are bigger. Fig. 3.22 shows the double gap time resolution as a function of the threshold which is given as fraction of the median signal. The figure also shows the signal height distribution. However, the lower limit of the threshold is determined by the noise. Raising the gas gain would help since the effective threshold would be lower but a higher gain is not desirable since the charge deposit in the chamber should be kept low to maximize the operating time of the detector. In 10 years of operation in the LHC environment with a gas gain of $10^5$ at 2.65 kV we can expect an accumulated charge of about 0.44 C/cm for the wires and 1.5 C/cm$^2$ for the cathodes. Raising the gas gain would also lead to increased space charge affecting the resolution.
2. **Measure the signal heights.** The height of the signal is correlated with the signal rise time. This is shown schematically in Fig. 3.17. The correlation between signal height and threshold crossing time is shown in Fig. 3.23 for 2000 simulated events. Using this information we can correct the time resolution. The result is also shown in Fig. 3.23. If we compare this corrected resolution with the uncorrelated one from Fig. 3.24(a), which is just the projection of the values in Fig. 3.23 on the time axis, we realize that we marginally improved the resolution. Since the threshold of 45 mV is quite low (≈ 3% of the median signal at 2.65 kV) the correlation is nearly lost and the influence of the time slewing effect is small (Fig. 3.16). In addition, the noise partially corrects for the time slewing as explained above. The operating thresholds in LHCb muon system are approximately twice as high (section 4.5). A time slewing correction for this case will be shown below as well as the influence of noise.

3. **Measure the induced charges.** The integral of the signal is also correlated with the threshold crossing time (Fig. 3.17). Fig. 3.23 shows the information which can be used to improve the time resolution. Again the improvement is only marginal.

4. **Apply a double threshold to the signal** and use the difference in threshold crossing times to measure the rise time. The method is shown schematically in Fig. 3.17. In our case Threshold 1 = 45 mV and Threshold 2 = 2 × Threshold 1. Fig. 3.23 shows the correlation which is used to correct for the time slewing. Using this information one could arrive at an improvement of about 5% for the time resolution.
Figure 3.23: The plots on the left show the correlation between signal height, induced charge (signal integral), threshold crossing time difference and threshold crossing time for an operating threshold of 45 mV (≈ 3% of the median signal at 2.65 kV). If we use this information we can correct for the time slewing and improve the time resolution. The results are shown on the right side. If we compare these histograms with the one from Fig. 3.24(a) we realize that the best way to correct for the time slewing is to use a double threshold. In this case one can arrive at an improvement of 5%.
It was shown above that the best way to correct for the time slewing is to use a double threshold. This method will be used to study the improvement one can make at an operating threshold of 7% of the median signal at 2.65 kV. A higher threshold also means increased time slewing. If we look again at Fig. 3.17 we used Threshold 1 = 105 mV and Threshold 2 = 2 × Threshold 1, we measured $t_1$ and $t_2$ and calculated the difference in threshold crossing time $t_2 - t_1$.

The results are shown in Fig. 3.25 and should be compared with Fig. 3.24(b) which shows the uncorrected time resolution turning off the noise and including all effects. Taking into account all effects one could arrive at an improvement of 7% for the time resolution of a double gap chamber.

As mentioned above, the effect of electronics noise is strongly correlated with the influence of charge fluctuations. Charge fluctuations result in reduced time resolution by causing threshold crossing time fluctuations (time slewing). Electronics noise partially compen-
Figure 3.25: The plots show the information that can be used to correct for the time slewing and the corrected time resolution for a threshold of 105 mV ($\approx 7\%$ of the median signal at 2.65 kV). The first two plots show the results including all effects, the other plots indicate the improvement if we turn off the effect of electronics noise. Noise results in additional threshold crossing time fluctuations and partially compensates for the time slewing and affects the correlation which we use for the correction. Comparing these results with Fig. 3.24(b) shows an improvement in time resolution of $7\%$ and $11\%$ respectively.
sates for this effect. For long signal rise times it shifts the threshold crossing times on average to smaller values. For short rise times this shift is on average smaller since the angle between the leading edge of the signal and the threshold is bigger (Fig. 3.17). Turning off the noise in the simulation and applying a double threshold lead to a better correlation between the threshold crossing times which can be used to correct for the time slewing. Comparing Fig. 3.25 and Fig. 3.24(b) one can realize that the time resolution can be improved by nearly 0.5 ns.

3.5 Discussion of results

A detailed detector simulation of the LHCb muon chambers has been performed in order to fully understand the detector and to be able to optimize the operating parameters. The simulations were done for the final MWPC geometry and for the gas mixture Ar/CO₂/CF₄ 40/50/10. The good agreement with actual measurements indicates that the procedure could also be used to study other gas mixtures. The time resolution limiting parameters such as detector capacitance, diffusion, charge and cluster position fluctuations, electronics noise, track position and wire spacing have been studied separately.

Ionization fluctuations have a big influence on the time resolution because of the time slewing effect. Decreasing the wire pitch to 1.5 mm results in improved time resolution but is not desirable because of potential instability problems and is not needed to fulfill the system requirements. We saw that the chambers should be operated at the lowest possible threshold to achieve the best time resolution and efficiency. A time resolution of 3.5 ns and an efficiency of 99 % within a 20 ns time window can be achieved if the threshold is set to ≈ 10 % of the median signal. However, the threshold is determined by the noise and by the fact that the detector should also be operated at the lowest possible high voltage in order to reduce the charge deposit and space charge effects in the chamber.

Applying a double threshold to the signal one can correct for the time slewing effect and improve the time resolution, as well as reduce the threshold dependence. The effect of
the correction is bigger for higher thresholds because of increased time slewing. Elec-
tronics noise affects the time slewing corrected resolution. For the LHCb muon system
an improvement of $\approx 7\%$ at the operating threshold is not worth the effort. A time
slewing correction is not needed since it is possible to set individual thresholds per front-
end channel and to correct for single noisy channels by just raising the threshold of the
channel concerned. However, for other large systems, like for example the ATLAS muon
spectrometer, a time slewing correction can dramatically improve the resolution [27].
Chapter 4

Optimization of the threshold settings of the LHCb muon system

In the last chapter we saw that the MWPCs of the LHCb muon system should be operated at the lowest possible threshold in order to achieve the best performance. This chapter will concentrate on the optimization of the operating thresholds of the LHCb muon system. In the past the thresholds have been set using an average threshold value for all the front-end (FE) channels of a region. The disadvantage of this procedure is that one cannot take into account the non-uniformity of separate channels and therefore one will always have some noisy channels within one region unless one raises the threshold for the whole region, which is of course not desireable. Since the FE electronics allow to set individual thresholds it is no problem to evaluate the thresholds taking into account the specific properties of each channel and apply them to the system.

In the following a method which allows to determine the optimal thresholds for the 122k front-end channels of the muon system will be presented. These thresholds keep the whole system at a low noise rate while conserving full efficiency and good time resolution. This will be the first step in order to optimize the LHCb muon system. In a next step one has to concentrate on the HV settings since the muon system should be operated for 10 years in a hostile environment without significant ageing. Therefore the system should not only be operated at the lowest possible threshold but also at the lowest possible gas
gain, i.e. high voltage. However, in the first phase of operation one can concentrate on
the threshold settings since the particle rates are still rather low and ageing doesn’t play
a major role. Therefore the HV settings are not discussed here in detail.

4.1 Equivalent noise charge

The front-end electronics of the muon system can be described by their delta response
[11]. The delta response $f(t)$ is given by injecting a delta signal to the electronics input
and measuring the output signal. If we want to calculate the output of the front-end
electronics $g(t)$ for a induced current signal $i(t)$ produced by a traversing particle we can
perform a convolution with the electronics delta response. The output is given by

$$g(t) = \int_0^t f(t - t')i(t')dt' \quad (4.1)$$

where $f(t)$ can be written as

$$f(t) = n^{-n}e^n \left( \frac{nt}{t_p} \right)^{n} e^{-\frac{nt}{t_p}} \quad (4.2)$$

In Eq. 4.2 $t_p$ is the peaking time of the amplifier and $n$ corresponds to the number of
integration stages in the electronics circuit.

Another important parameter which characterizes the front-end electronics is the Equiv-
alent Noise Charge (ENC). The ENC is defined as the signal charge which results in a
signal to noise ratio of unity. It can be written as [11]

$$\text{ENC}^2 = \frac{1}{2} e_n^2 C^2 \int_{-\infty}^{\infty} f'(t)^2dt + \frac{1}{2} i_n^2 \int_{-\infty}^{\infty} f(t)^2dt = \frac{\sigma_v^2}{g^2} \quad (4.3)$$

where $C$ is the detector capacitance, $e_n$ and $i_n$ are the serial and parallel spectral noise
densities of the front-end electronics, $f(t)$ is the normalized delta response, $\sigma_v^2$ describes
the variance of the noise and $g$ is the sensitivity. The spectral densities have values of
$e_n \approx 1 - 2 \text{ nV}/\sqrt{\text{Hz}}$ and $i_n \approx 2 - 3 \text{ pA}/\sqrt{\text{Hz}}$. The sensitivity $g$ gives the output peak
Figure 4.1: The plots show the equivalent noise for CARIOCA positive (cathode readout) and negative (wire readout). The ENC has been determined by injecting a given charge to the electronics input.

voltage $v(t_p) = gQ$ for an input current pulse $i(t) = Q\delta(t)$. For the front-end electronics of the muon system $g$ is of the order of a few mV/fC. Since the noise r.m.s. is given by $\sigma_v = g\text{ENC}$ we will get an output pulse with a height equal to $\sigma_v$ if we inject a signal with the charge $Q = \text{ENC}$. For any given delta response $f(t)$ and a given peaking time $t_p$ the above integral can be evaluated to

$$\text{ENC}^2 = \frac{1}{2} e_n^2 C^2 \left( at_p \frac{i_n^2}{e_n^2 C^2} + \frac{b}{t_p} \right) \quad (4.4)$$

where $a$ and $b$ depend on the shape of the delta response.

Fig. 4.1 shows the ENC as a function of the input capacitance for CARIOCA positive (cathode readout) and negative (wire readout). The sensitivity $g$ can be determined by injecting a given charge to the electronics input and measuring the corresponding output voltage. After measuring $\sigma_v$ the ENC can be evaluated using Eq. 4.3. The ENC has been determined for different capacitances by connecting additional capacitors to the
same CARIOCA channel. The equivalent noise at 0 capacitance is about 2060 electrons and increases with 45 e/pF for the positive chip. For the negative polarity one gets: 

\[
\text{ENC} = 2080 \ e + 46 \ e/pF.
\]

It is obvious from the above discussion that the ENC is a very important parameter of the system and that the electronics should be optimized in the sense that the ENC should reach a minimum in order to achieve the best performance. The ENC characterizes the front-end electronics noise and imposes a lower limit on the threshold and therefore influences the time resolution and efficiency of the chambers.

Monitoring and evaluation of the ENC allow to determine how the system changes in time during operation in the high rate environment of the experiment and help to set optimal thresholds in the system in order to keep the noise at an acceptable level while conserving high efficiency and good time resolution. Since we have a large spread in detector capacitance in the muon system and even capacitance variations between the channels of one FE board [28], and since the channels show other differences in their characteristics, the ENC varies from channel to channel.

### 4.2 ENC calculation in the muon system

It was shown before that the ENC can be determined by injecting a given charge to the electronics input and measuring the output signal. However, it’s not possible to use this method in the muon system and therefore another procedure must be adopted.

The method described in the following is currently used in the muon system and is based on evaluating the ENC for a single CARIOCA channel by analyzing the noise distribution of the channel obtained from a threshold scan [21]. The results are consistent with the ones obtained by the charge injection method and allow to set the optimal operating thresholds.
Figure 4.2: Output histogram of a threshold scan for one channel of a M3R3 chamber. The position of the maximum determines the channel offset.

Threshold scan

The threshold scan gives information about the noise present at each of the 122112 front-end (FE) channels of the muon system. The procedure is done without injecting a signal to the electronics which means that only the noise is present. The scan works in the following way: the threshold is scanned over a given range (usually 30 to 150 r.u.) in steps of 1 r.u. and for each step the corresponding noise rate is measured in a gate time of usually 200 ms. This is repeated for each channel. While measuring one channel, all the other FE channels are kept at the highest possible threshold, i.e. 255 r.u., in order to avoid that channels influence each other via cross talk where high counting rates on one channel cause some extra hits on the neighbouring ones.

The output histogram of a threshold scan is shown in Fig. 4.2 for one channel of a chamber of station M3R3. One can see that the maximum noise rate is not at zero threshold as one would expect. This is due to an offset which is a feature of the CARIOCA chip. Fig. 4.3 is reproduced from [21] and shows schematically the situation. The offset is referred
Figure 4.3: The plot shows a gaussian noise distribution reconstructed by using the threshold scan raw data. The offset and the discriminator bias vary from channel to channel.

\[
\begin{align*}
    f_0 \exp \left( -\frac{(x - \mu)^2}{2\sigma^2} \right) &; \mu = 0 \\
    f_0 \exp \left( -\frac{(x - \mu)^2}{2\sigma^2} \right) &; \mu = 0
\end{align*}
\]

Figure 4.4: Centralization and linearization of the noise distribution. The ENC can be evaluated by using the slope of the straight line.

\[
\text{ENC} = \frac{0.466}{\sqrt{|\text{slope}|}}
\]
to as the position of the maximum of the noise histogram obtained from the threshold scan. However the offset determined this way is not the real offset since there is also a bias which is called minimum detectable charge and which is due to the discriminator stage of the FE electronics [29]. Because of this discriminator bias it is not possible to measure the position of zero threshold directly. Both parameters, the real offset and the bias, show a spread from channel to channel.

**Rate at zero threshold**

The noise distribution in Fig. 4.3 can be described by a Gaussian [21] with a mean $\mu = \text{offset} - \text{bias}$ and a r.m.s. $\sigma = \text{ENC}$ and the rate at a threshold $Q_{th}$ is given by

$$f = f_0 \exp \left[ -\frac{Q_{th}^2}{2\text{ENC}^2} \right]$$  \hspace{1cm} (4.5)

where $f_0$ is the rate at zero threshold which is related to the bandwidth of the CARIOCA chip as shown in the following. The average frequency of zero crossings of a random noise signal is given by Rice’s formula [18].

$$f_{\text{zero}} = 2 \sqrt{\frac{\int_{0}^{\infty} f^2 w(f)df}{\int_{0}^{\infty} w(f)df}}$$  \hspace{1cm} (4.6)

In Eq. 4.6 $w(f)$ is the noise power spectrum which is constant in our case and given by $e_n$ and $i_n$. If we assume in addition a bandwidth extended from $f_a$ to $f_b$ we can evaluate the average rate of zero crossings to

$$f_{\text{zero}} = 2 \sqrt{\frac{\frac{1}{3}(f_b^3 - f_a^3)}{f_b - f_a}}$$  \hspace{1cm} (4.7)

and since the discriminator only counts for crossings in one direction the rate at zero threshold $f_0$ is given by

$$f_0 = \frac{f_{\text{zero}}}{2}$$  \hspace{1cm} (4.8)
Figure 4.5: The plots illustrate the procedure to determine the rate at zero threshold. Performing a threshold scan on a CARIOCA channel for two different capacitances is sufficient to define $f_0$. One can also use the spread in detector capacitance from channel to channel to find the rate at zero threshold without connecting another capacitor.

and has been determined to $f_0 = 25$ MHz or on a logarithmic scale $y_0 = \log f_0 \approx 7.4$ [30]. It can be found by performing a threshold scan on a CARIOCA channel for two different detector capacitances ($C_{det}$ and $C_{det}$ plus additional capacitor in parallel).

Fig. 4.5 illustrates the method. By choosing a quadratic scale on the x-axis and a logarithmic scale on the vertical axis one can present the output of the threshold scan by a straight line. The crossing point of the two lines defines the position of zero threshold and the corresponding rate $f_0$. Since there is a spread in $C_{det}$ from channel to channel one could also use all the channels of a front-end board to determine the rate at zero threshold. $f_0$ is also called the fundamental frequency of the CARIOCA chip.

Once defined, the rate at zero threshold $f_0$ will be used as a fixed parameter for the whole system. Although the accuracy of the measurement of this rate is not to high and it is clear that $f_0$ will not be the same for all the CARIOCA chips of the muon system, one can use a constant value of 25 MHz. As will be shown later the consequences of $f_0$ fluctuations are marginal.
Figure 4.6: The plots show the equivalent noise for CARIOCA positive (cathode readout) and negative (wire readout). The ENC has been determined by analysing the noise distribution obtained from a threshold scan.

Centralization and linearization

In order to extract the ENC from Eq. 4.5 we centralize and linearize the Gaussian. By doing so we can also obtain a value for the discriminator bias and in consequence the real offset is determined. Fig. 4.4 shows the procedure of centralization and linearization. We start from Eq. 4.5 and then use a logarithmic scale for the vertical axis and a quadratic scale for the horizontal axis.

\[
f = f_0 \exp \left[ -\frac{1}{2} \left( \frac{Q_{th}}{\text{ENC}} \right)^2 \right]
\]

\[
\log f = \log f_0 - \log e \cdot \frac{Q_{th}^2}{2\text{ENC}^2}
\]

\[
y = y_0 - \log e \cdot x
\]  

(4.9)

The bias is found by moving the straight line from Eq. 4.9 to the left until the y-intercept equals \(\approx 7.4\) since \(y_0\) gives the rate at zero threshold. The ENC can be calculated by
Figure 4.7: The plot shows the linearization procedure for one channel of a M3R3 chamber. The y-intercept $y_0 = \log f_0 \approx 7.4$.

using the slope of the straight line.

$$ENC = \sqrt{\frac{\log e}{2|\text{slope}|}} = 0.466$$  \hspace{1cm} (4.10)

Now one can evaluate the equivalent noise for different detector capacitances and compare the results with the ones obtained in section 4.1 where the ENC was determined by injecting a given charge to a CARIOCA channel. In order to perform the analysis a threshold scan was performed on the same CARIOCA channel connecting different capacitors to the input. The results are shown in Fig. 4.6 for CARIOCA positive and negative. For the positive (negative) polarity one gets: ENC = 2000 e + 41 e/pF (ENC = 1990 e + 42 e/pF). The agreement with the results obtained by the charge injection method (Fig. 4.1) is quite good, the small difference between the capacitive noise terms can be explained by the fact that the sensitivity is measured with an accuracy of 5 – 10%. The consistency of the two methods implies that the threshold scan analysis can be used to determine the ENCs for the whole muon system.
Figure 4.8: The figure shows the output histogram of a threshold scan for one channel of a M4R4 chamber. The position of the maximum determines the channel offset.

Figure 4.9: The plot shows the linearization procedure for one channel of a M4R4 chamber. The y-intercept $y_0 = \log f_0 \approx 7.4$. 

Threshold Scan Fit for chamber M4A_5A, FEB00, Channel01

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<thead>
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<th>Entries</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
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</tr>
<tr>
<td>RMS</td>
<td>2.908</td>
</tr>
<tr>
<td>Underflow</td>
<td>0</td>
</tr>
<tr>
<td>Overflow</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 4.1: Parameters extracted from the noise distribution obtained from the threshold scan performed on a M3R3 and a M4R4 chamber.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber</td>
<td>M3R3</td>
</tr>
<tr>
<td>Readout type</td>
<td>Cathode pads</td>
</tr>
<tr>
<td>Capacitance</td>
<td>91 pF</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>11.7 mV/fC</td>
</tr>
<tr>
<td>Offset</td>
<td>74 r.u.</td>
</tr>
<tr>
<td>Bias</td>
<td>11.7 r.u.</td>
</tr>
<tr>
<td>Slope</td>
<td>0.0087</td>
</tr>
<tr>
<td>ENC</td>
<td>4.99 r.u.</td>
</tr>
<tr>
<td>ENC</td>
<td>1.00 fC</td>
</tr>
<tr>
<td>ENC</td>
<td>6263 e</td>
</tr>
<tr>
<td>Capacitive noise</td>
<td>46.2 e/pF</td>
</tr>
</tbody>
</table>

Examples

Fig. 4.2 shows the output histogram of a threshold scan performed on a FE channel of a chamber of station M3R3. Fig. 4.7 shows the same channel after linearization and centralization of the noise distribution as described above. Fig. 4.8 and Fig. 4.9 show another example of a M4R4 chamber.

Table 4.1 summarizes the parameters obtained from the analysis. The offset is the maximum of the noise histogram in Fig. 4.2 and Fig. 4.8 respectively. The ENC is calculated from the slope of the straight line and is given in r.u., fC and electrons (e). To calculate these parameters we need the detector capacitance and the sensitivity which are given in the table. The capacitive noise terms agree well with the results from the measurements presented in section 4.1.

$f_0$ fluctuations

Assuming a rather large $f_0$ variation of \( \pm 10\% \), leading to $y_0 = \log(22.5 \text{ [MHz]}) \approx 7.35$ and $y_0 = \log(27.5 \text{ [MHz]}) \approx 7.44$ one can evaluate other important parameters like the bias, ENC and threshold.
**Figure 4.10:** The plots show the parameters obtained from the threshold scan analysis for M3R3 assuming variations of the fundamental frequency $f_0$ of $\pm 10\%$. The final threshold which is calculated by using the offset, the bias and the ENC is not affected by the fluctuations.

Fig. 4.10 shows the distribution of the bias, the slope of the straight line which is used to calculate the ENC and the final threshold for M3R3. It will be explained in more detail in the next section how the threshold is calculated but what is important to realize here is that for a $f_0$ fluctuation of $\pm 10\%$ the bias only varies by $\pm 2\%$, the ENC by approximately $\pm 0.5\%$ and the set threshold is in principle the same. This implies that a constant value $f_0$ can be used.
4.3 Threshold setting

Once the parameters are determined as described above the threshold for the analysed FE channel can be set according to Fig. 4.3 as

\[ \text{Thr [r.u.]} = \text{offset [r.u.]} - \text{bias [r.u.]} + n \times \text{ENC [r.u.]} \quad (4.11) \]

In order to determine \( n \) we can estimate the noise by using the equation of the straight line in Fig. 4.7 for example. Typically thresholds are set to 5 or 6 times the ENC because the noise should be suppressed at these threshold levels. So if we try \( n = 5 \) and use the values from Table 4.1 and Eq. 4.9 we get \( y \approx 2 \). So the expected noise rate is approximately 100 Hz which would be satisfying as long as we deal with single channels.

If we look at a system with more than 120000 channels we also have to take into account that the channels influence each other and that we have to deal with coherent noise effects. Moreover there are of course fluctuations in the sensitivity from CARIOCA chip to CARIOCA chip and other channel to channel variations. In fact the system should be in a better state with a threshold given by \( 6 \times \text{ENC} \) where we expect a noise rate below 1 Hz. Nevertheless one should always keep an eye on efficiency and time resolution since the threshold directly influences these parameters. The influence of the threshold on efficiency and time resolution is shown and discussed in section 4.5.

To conclude we can say that at \( 6 \times \text{ENC} \) the system should be in an optimal state with respect to noise, \( 5 \times \text{ENC} \) is the minimal threshold that can be used for some channels or regions and at \( 7 \times \text{ENC} \) we get close to the limit where the time resolution and efficiency might be affected.

**Threshold setting in the past**

In the past the thresholds of the muon system were set according to

\[ \text{Thr [r.u.]} = \text{offset [r.u.]} - \text{bias}_{\text{const}} [\text{r.u.}] + n \times \text{ENC}_{\text{avg}} [\text{r.u.}] + S_{\text{coh}} \quad (4.12) \]
using \( n = 6 \), an offset per channel, a constant value of 11 r.u. for the bias and an ENC per region. In addition \( S_{coh} = 2 - 5 \text{ r.u.} \) was added to get rid of coherent noise effects due to some noisy channels. This is not needed if the ENC and bias are calculated per front-end channel since the channel characteristics are represented by these parameters.

### 4.4 Multi channel analysis

Up to now we just discussed and used the method for single channels of the system and determined the parameters like offset, bias or ENC “by hand” by looking at the noise histogram or using the above equations. But since we have more than 120000 channels in the muon system and since we aim to set individual thresholds for each channel in order to take into account the channel to channel variations described above, we first of all need a software tool which simplifies the analysis.

Once the analysis tool is ready and the threshold scan data are collected, the threshold files with the 122k thresholds can be provided within half an hour. The method explained before on single channel examples works very well for 99 % of all the front-end channels and allows to determine the optimal thresholds for almost the whole system.

Since we have to deal with a very large system it is obvious that there are some channels where the method doesn’t work as smoothly as in the examples above or doesn’t work at all which is especially true for regions where the detector capacitance is very low. These limits of the method will be discussed.

Furthermore we have to take into account the large spread in detector capacitance as well as the different readout types we have in the muon system. In addition there will be some channels which are very noisy and need higher thresholds. This means that a threshold of \( 6 \times \text{ENC} \) won’t work for the whole system and therefore some fine tuning is needed. To check if the thresholds are optimal we will look at the noise present in the system as well as at efficiency and time resolution.
4.4.1 Analysis tool

In order to analyse a large number of channels and get the desired information quickly a software tool called NOEMI (NOise EMbedded Inspector) [31] was used. The method for ENC calculation as described before was implemented in the program as well as a routine which calculates the optimal thresholds and the expected noise for the whole system. The results are written to files that can be uploaded on the system in order to create threshold values for the whole muon detector.

The program offers different ways to analyze the threshold scan data:

- **Single channel analysis:** The parameters like offset, bias, ENC and threshold are calculated for a single channel by linearizing and centralizing the noise distribution.

- **Single front-end board analysis:** A selected parameter is calculated for the 16 channels of the selected FE board and the distribution is shown.

- **Single chamber analysis:** Every channel of a selected chamber is analyzed and the distribution of the selected parameter is shown.

- **Many chamber analysis:** The distribution of the selected parameter is shown for specified chambers, a whole region, a whole quadrant, a full station or the whole system.

- **Complete analysis:** Calculates all parameters for specified chambers, regions, etc. and writes them to a file.

- **Operating threshold calculation:** The optimal thresholds are calculated for a specified part of the system and written to a file which can be used directly to set the thresholds in the muon system.

The NOEMI tool is also quite powerful to debug the system since one can see from the parameter distributions if chambers or regions have problems like noisy or dead channels. The single FE board or the single channel analysis can provide useful information in such
cases. Fig. 4.11 shows the main window of the NOEMI program with a single channel analysis of the M3R3 chamber which we have analysed in section 4.2.

4.4.2 Tuning of the method

If we look at Fig. 4.2 or Fig. 4.8 it is evident that we have to ensure that we only fit the central part of the noise histogram, i.e. a part around the offset where the rate exceeds a defined minimum. Otherwise we couldn’t perform the linear fit because in the outer regions of the histogram the rate is about the same for different thresholds while in the central region we have a slope. In order to select the range we want to use for the analysis we demand a minimum rate and a maximum number of points.
The plot shows the noise histogram of a channel of a M4R4 chamber and gives an example for the tuning of the method. If we concentrate on the right edge of the histogram one should demand a minimum rate of about 100 Hz and skip the last two bins to improve the quality of the linear fit.

Fig. 4.12 shows the noise histogram of a channel of a M4R4 chamber and gives an example to understand the procedure. For the analysis we concentrate on the right edge of the histogram. To determine the range used for the analysis we start at the highest threshold and go to the left, i.e. to lower thresholds. The first bin with a content larger than a certain minimum will be the first point used. From there we continue towards lower thresholds till we reach the last point which is the offset, i.e. the bin with the maximum content. In the example one should set a minimum rate of about 100 − 200 Hz to cut the events which are not interesting for the analysis. Furthermore one can realize that the contents of the central two bins (offset and the one before) are nearly the same while for the other bins the bin contents differ significantly. This will decrease the quality of the linear fit and therefore one should skip the last two bins or at least the last bin. If we call the bin index of the offset \( m \), we can say that we are using \( n = m − 2 \) points for the analysis. In Fig. 4.12 \( m = 17 \) for a minimum rate of 100 Hz.

In order to use this procedure on the scale of the whole system one has to define separate
Figure 4.13: The plot shows the noise histogram of a channel of a M1R3 chamber and gives an example for the limit of the method. The detector capacitance in this region is \( C_{\text{det}} = 51 \, \text{pF} \) and the noise histogram is very narrow. To achieve the best result one should apply a minimum rate of 20 Hz and skip the last bin (m - 1 points).

criteria for different regions by monitoring the fit quality. Different settings are needed because of the spread in detector capacitance and noise rate. The electrical capacitance and the particle rate of a pad must be limited to keep the noise and the dead time of the front-end channels to an acceptable level. This in fact determines the pad sizes for most of the regions of the muon system. Fig. 4.13 for example shows the output of a threshold scan performed in M3R3 where the detector capacitance is \( C_{\text{det}} = 51 \, \text{pF} \). In this case we cannot afford to demand a minimum rate of 100 Hz and skip the last two bins because there won’t be enough points left to perform the analysis. The values which were determined to give the best results are listed in Table 4.2.

4.4.3 Limits of the method

We saw already in section 4.4.2 that one has to define individual criteria for each region of the system for defining the noise histograms. This is simply because the noise distributions are different since in the muon system we have different detector capacitances due to
Table 4.2: Tuning values. The bin content should exceed a minimum rate. In addition a maximum number of points is used for the linear fit. W stands for wire readout, C for cathode readout and m is the index of the offset.

<table>
<thead>
<tr>
<th>Region</th>
<th>Minimum rate [Hz]</th>
<th>Number of points n</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1R1</td>
<td>20</td>
<td>m − 1</td>
</tr>
<tr>
<td>M1R2</td>
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<td>m − 1</td>
</tr>
<tr>
<td>M1R3</td>
<td>20</td>
<td>m − 1</td>
</tr>
<tr>
<td>M1R4</td>
<td>20</td>
<td>m − 1</td>
</tr>
<tr>
<td>M2R1W</td>
<td>40</td>
<td>m − 2</td>
</tr>
<tr>
<td>M2R1C</td>
<td>100</td>
<td>m − 3</td>
</tr>
<tr>
<td>M2R2W</td>
<td>40</td>
<td>m − 2</td>
</tr>
<tr>
<td>M2R2C</td>
<td>100</td>
<td>m − 3</td>
</tr>
<tr>
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<td>m − 2</td>
</tr>
<tr>
<td>M2R4</td>
<td>100</td>
<td>m − 5</td>
</tr>
<tr>
<td>M3R1W</td>
<td>40</td>
<td>m − 2</td>
</tr>
<tr>
<td>M3R1C</td>
<td>100</td>
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<td>M3R4</td>
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<tr>
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<td>m − 4</td>
</tr>
<tr>
<td>M4R4</td>
<td>800</td>
<td>m − 5</td>
</tr>
<tr>
<td>M5R1</td>
<td>100</td>
<td>m − 2</td>
</tr>
<tr>
<td>M5R2</td>
<td>600</td>
<td>m − 4</td>
</tr>
<tr>
<td>M5R3</td>
<td>600</td>
<td>m − 4</td>
</tr>
<tr>
<td>M5R4</td>
<td>700</td>
<td>m − 4</td>
</tr>
</tbody>
</table>

different pad sizes.

If one compares Fig. 4.13 which shows the output of a threshold scan performed on a M1R3 chamber ($C_{det} = 51$ pF) with Fig. 4.12 which shows the noise histogram of one channel of a M4R4 chamber ($C_{det} = 225$ pF) one can realize that for high detector capacitances the histogram is broader and has more entries to perform the analysis while for the low capacitances it is hard to do an accurate analysis. In some cases, in particular in the inner regions of stations M1, M2 and M3 where the pads are small and the detector capacitances low, the method even fails because the noise histograms don’t have enough entries.
In principle we can distinguish between three reasons which lead to a failure of the method:

1. **Empty noise histogram.** The threshold scan itself fails for \( \approx 0.2 \% \) of the channels and gives no output most likely due to some communication problems within the system.

2. **Too few entries in the noise histogram.** As mentioned above in the inner regions of stations M1, M2 and M3 the noise rate measured in the threshold scan is very low and the noise histograms are very narrow. If \( n \) is the number of points available for the analysis after the tuning procedure described in section 4.4.2 one can say that for \( n < 2 \) the method cannot be performed because the linear fit is not possible. This is the case for \( \approx 0.5 \% \) of the channels. Using both sides of the noise histogram one could increase the number of points but is not beneficial since it reduces the fit quality.

3. **Bad fit quality.** In order to prove the correctness of the obtained results one has to monitor the quality of the linear fit, i.e. the errors of the fit parameters. One can check the fit quality by looking at the correlation coefficient \( R \) which is given by

\[
R = \frac{n \sum_i (x_i y_i) - \sum_i x_i \sum_i y_i}{\sqrt{n \sum_i (x_i^2) - (\sum_i x_i)^2} \sqrt{n \sum_i (y_i^2) - (\sum_i y_i)^2}}
\]  

(4.13)

for data points \((x_i, y_i)\) with \( i = 1, \ldots, n \). The correlation coefficient takes values between 0 and 1, a value close to 1 indicates a good linear correlation. In our analysis we demand \( R^2 > 0.9 \) which is not the case for \( \approx 0.4 \% \) of the channels.

In total there are 1300 channels (\( \approx 1.1 \% \) of all channels) where the method failed because of the above reasons. In order to evaluate the threshold we take the average values for the offset, bias and ENC of the regions concerned which are obtained by analyzing the other channels of the region where the method did work. If the noise histogram is empty which means that the threshold scan failed one has to take average values for all three parameters. In cases where the method failed because of too few entries or a bad fit
quality one can take at least the correct offset from the histogram.

Table 4.3 summarizes the numbers of skipped channels for the different regions. In Table 4.4 the average values which are used if the method fails are listed as well as the values for the detector capacitance and sensitivity. The last column gives the average thresholds calculated according to Eq. 4.11. When looking at the two tables one can see that most of the skipped channels are found in regions with a capacitance around or below 80 pF.

4.5 Application of the method

Fig. 4.14 shows the distributions of the offset, bias, ENC, fundamental frequency $f_0$ and threshold for region R3 of station M3. The mean values of the distributions of the stated parameters for all the regions of the muon system are listed in Table 4.4.

Offset

One can see from Fig. 4.14 that the offset varies between 50 and 100 r.u. which is basically the same for all the regions of the system. However, within one region we have to deal with large offset variations from FE channel to FE channel which have to be taken into account properly to determine the optimal thresholds. The 17 skipped channels correspond to the 17 channels in M3R3 for which the threshold scan didn’t work, i.e. no entries in the noise histogram (Table 4.3). For these channels the mean values of the region concerned have been taken to evaluate the operating thresholds.

Bias

One can see that the bias or minimum detectable charge which is due to the discriminator stage of the CARIOCA chip and which has been assumed constant in the past is not constant at all but also shows quite large channel to channel variations within one region. The average bias of the whole system is $\approx 10 - 11$ r.u.. The 27 skipped channels now
Table 4.3: Skipped channels. For 1.1% of all channels the threshold scan analysis cannot be performed and the average values which are listed in Table 4.4 are used to determine the threshold.

<table>
<thead>
<tr>
<th>Total number of channels</th>
<th>Bad fit ((R^2 &lt; 0.9))</th>
<th>Too few points ((n &lt; 2))</th>
<th>No entries</th>
<th>In total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(N^\circ) of channels</td>
<td>(N^\circ) of channels</td>
<td>(N^\circ) of channels</td>
<td>(N^\circ) of channels</td>
</tr>
<tr>
<td>M1R1W</td>
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<td>143</td>
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<td>1</td>
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<td>M1R2C</td>
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<td>32</td>
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</tr>
<tr>
<td>M1R3C</td>
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<td>92</td>
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<td>24</td>
</tr>
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<td>8</td>
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<tr>
<td>total</td>
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<td>590</td>
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Table 4.4: The table summarizes the average values which are obtained by analyzing all the channels of one region.

<table>
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<th>Cdet</th>
<th>Sens</th>
<th>Offset</th>
<th>Bias</th>
<th>ENC</th>
<th>ENC6</th>
<th>6ENC</th>
<th>Thr</th>
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<td>1.01</td>
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<td>1.08</td>
<td>28.98</td>
<td>6.49</td>
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<tr>
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<td>9.49</td>
<td>2.86</td>
<td>0.59</td>
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<td>3.57</td>
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<td>7.47</td>
</tr>
<tr>
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<td>74.60</td>
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<td>5.14</td>
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<td>30.84</td>
<td>7.47</td>
</tr>
</tbody>
</table>
Figure 4.14: The plots show the results of the threshold scan analysis performed on all the channels of M3R3. The skipped channels correspond to the channels listed in Table 4.3 for which the analysis method failed.
correspond to the channels in M3R3 for which the analysis method didn’t work at all because of a bad linear fit quality, noise histograms with too few entries for the analysis or no data from the threshold scan (Table 4.3).

**ENC**

One can realize from Table 4.4 that the ENC is higher for larger detector capacitance, i.e. larger pad size, as expected. Of course this behaviour affects the threshold. The ENC is given in r.u. and in fC. One can convert the values by using the sensitivity which is given in the table.

**Fundamental frequency** $f_0$

Fig. 4.14 also shows the distribution of the logarithm of the fundamental frequency $f_0$ of the CARIOCA chip ($y$-intercept $y_0 = \log f_0$). As expected the distributions are centered around $\log f_0 = 7.4$ since we demand that the rate at zero threshold $f_0$ is $\approx 25$ MHz. It was shown in section 4.2 that a 10 % variation in $f_0$ doesn’t affect the final threshold settings and therefore the rate can be used as a fixed parameter in the analysis.

**Threshold**

The distribution of the set threshold for M3R3 is shown in Fig. 4.14. The thresholds have been calculated according to the following equation. In case the method failed the average values listed in Table 4.4 have been used.

$$\text{Thr [r.u.]} = \text{offset [r.u.]} - \text{bias [r.u.]} + n \times \text{ENC [r.u.]}$$  \hspace{1cm} (4.14)

For most parts of the system we chose $n = 6$. Only for region R1 and R2 of station M2 and M3 where we have combined wire and cathode readout, we decided to have different settings only for the wires to have approximately the same thresholds within one region and to avoid noisy channels. Since in region R2 of station M2 and M3 the capacitance of
Figure 4.15: The plot shows a comparison between the thresholds used in the past and the new thresholds for M3R3. The thresholds used at present are on average lower since the individual settings for bias and ENC allow to take into account the specific properties of each channel and therefore one can set the optimal thresholds.

wires and cathodes is comparable and the anode signals are twice as high as the cathode signals one can chose \( n = 12 \) for the wires. In region R1 the wire capacitances are small compared to the cathodes and therefore \( n = 9 \) is sufficient.

In the past the thresholds have been set according to Eq. 4.12 using a constant value for the bias and the average ENC of a region. Fig. 4.15 shows a comparison between the thresholds used in the past and the new thresholds for M3R3. The thresholds used at present are on average 5 r.u. (≈ 11 mV) lower. This corresponds to approximately 1 fC.

The width of the distribution can be explained by the fact that in contrast to the old settings we consider bias and ENC variations (Fig. 4.14) which contribute with about 1 r.u. each.

Fig. 4.16 shows the pulse height distribution of 2000 simulated events in a double gap filled with the operating gas mixture Ar/CO\(_2\)/CF\(_4\) 40/55/5 operated at 2.65 kV. With 100 pF an average detector capacitance of a R3 chamber was chosen. The simulation was
Figure 4.16: The plot shows the simulated pulse height distribution in a double gap filled with the operating gas mixture Ar/CO$_2$/CF$_4$ 40/55/5 operated at 2.65 kV. With 100 pF an average detector capacitance of a R3 chamber was chosen. The median pulse height is 1418 mV. The highest thresholds correspond to $\approx 10\%$ of the median signal, the lowest ones to $\approx 2\%$ of the median.

The median signal height is 1418 mV. If we look at Fig. 4.14 and use the values in Table 4.4 we see that the average threshold in M3R3 is $6 \cdot$ ENC$_{\text{avg}}$ [fC] $\cdot$ sens [mV/fC] $\approx$ 58 mV ($\approx 4\%$ of the median signal). The thresholds in this region go up to 84 mV ($\approx 6\%$ of the median signal) and down to 35 mV ($\approx 2.5\%$ of the median signal). The highest thresholds are set in M2R2 where we use 12ENC for the wires. There the thresholds are set up to $\approx 9.5\%$ of the median signal. In M1R3 the thresholds are very low and correspond to $\approx 2-2.5\%$ of the median signal. To conclude we can say that the thresholds of the muon system are set to $\approx 2-10\%$ of the median signal depending on the region. This shows that the values for the thresholds are quite reasonable.
4.6 Discussion of results

The Multi Wire Proportional Chambers of the LHCb muon system should be operated at the lowest possible threshold. In order to find the optimal thresholds one has to take into account the large spread in detector capacitance due to different chamber types, the variations of front-end (FE) channel offsets and a bias due to the discriminator stage of the CARIOCA chip. The method which was used to determine the operating thresholds is based on a centralization and linearization of the noise distribution obtained from the threshold scan and uses the fundamental frequency $f_0 = 25 \text{ MHz}$, which is related to the bandwidth of the CARIOCA chip, as a reference point. The procedure allows to set thresholds per FE channel and to take into account the specific properties of the individual channels. The method was applied to the whole system and it was shown that the obtained threshold values are reasonable with respect to expected signal heights during operation.

Fig. 4.17 shows a comparison between the threshold settings of the past and the new threshold settings, i.e. a comparison between the threshold values calculated according to Eq. 4.12 and Eq. 4.11. The analysis has been done for the whole muon system except for M1R1. The GEM chambers are not included since there were no existing threshold settings from the past.

Generally the new thresholds are lower since it is not necessary to add another $0.5 - 1 \text{ fC}$ (approximately $2 - 5 \text{ r.u. and } \approx 5 - 11 \text{ mV}$) to all the thresholds of a region like it was done in the past. Considering not only the offset variations but also the bias and ENC variations allows to take into account the specific properties of each channel and to set optimal thresholds. For the regions R1 and R2 of stations M2 and M3 where we have combined readout the difference between old and new thresholds is quite big ($20 - 30 \text{ r.u. } \approx 5 - 6 \text{ fC for the wires}$). This can be explained by the fact that in the past the thresholds of the wires have been calculated by just doubling the cathode thresholds. Now the wire thresholds are set according to $n \times \text{ENC}$ with $n = 9$ ($n = 12$) for M23R1 (M23R2).
Fig. 4.17: The plot shows a comparison between the threshold settings used in the past and the new threshold settings. The new thresholds are in general lower. The small second maximum corresponds to the regions R1 and R2 of stations M2 and M3 where the differences are quite big.

Fig. 4.17 indicates that on average one can lower the thresholds by $\approx 0.5 - 1 \text{ fC}$ if one uses individual settings per front-end channel. In a next step one should check if the noise in the muon system can be kept to an acceptable level with these thresholds. The Experiment Control System (ECS) of the LHCb muon system allows to monitor all the channels of the system and can determine noise levels and dead channels. Fig. 4.18 was taken from [32] and shows the noise level for the whole muon system. The results show that for 99.3% of all channels the noise is completely suppressed and that for 99.8% of the channels the noise rate is below 1 kHz which we consider as the limit for some channels of the muon system. Some channels (0.2%) are rather noisy. These are pathological channels or front-end chips which are always present in such a big system. Also the selection criteria when testing the chips were not optimized with respect to noise performance [33]. The problem can be solved by raising the threshold for the channels concerned.

The results obtained by monitoring the noise with the ECS are very promising and indicate
Figure 4.18: The plots show the results obtained by monitoring the noise of the muon system with the Experiment Control System (ECS). 99.8% of the channels show a noise rate below 1 kHz.

Figure 4.19: The plot shows the influence of the threshold on the efficiency and time resolution of a double gap and a 4-gap chamber. The results for the 4-gap are obtained by performing the logical OR of two double gaps. Since the operating thresholds are set to 2 – 10% of the median signal we expect an efficiency > 99% and a time resolution < 3.5 ns for the double gap.
that on one hand the thresholds are high enough to keep the noise of the front-end channels to the desired level. In a next step we should look at the time resolution and efficiency to be sure that on the other the thresholds are also low enough to fulfill these requirements.

Fig. 4.19 shows the efficiency and time resolution as a function of the threshold which is given as fraction of the median signal. The results have been obtained by using the drift chamber simulation program GARFIELD [1] (section 3.1.1). The median pulse height is 1418 mV and has been determined by using the signal height distribution shown in Fig. 4.16. The simulations were done for the gas mixture Ar/CO$_2$/CF$_4$ 40/55/5 and a high voltage of 2.65 kV (gas gain $G = 10^3$). One can see that with the operating thresholds which are set to 2 – 10 % of the median signal we expect to achieve the required double gap time resolution $< 3.5$ ns and an efficiency $> 99 \%$. 


Chapter 5

Performance of the LHCb muon system

The discussions in the last chapters gave information about the expected performance of the LHCb muon system. In the following we will have a short look on the time resolution and efficiency of the muon detector obtained by analysing cosmics data as well as first collision data aquired in LHCb at the end of 2009.

5.1 Cosmic rays

Cosmic particles have played a very important role in the commissioning of the LHCb detector. Unfortunately the experimental setup is not well suited for cosmic runs since the rate of tracks within the acceptance of the detector (±250 mrad from the horizontal) is well below 1 Hz. However, several cosmic runs have been performed, resulting in several million cosmic events recorded by the experiment. For the muon system this was enough to provide a good spatial alignment and a first time alignment and to have a first look on the performance of the detector.
5.1.1 Time alignment

In order to achieve the required efficiency the MWPCs of the muon system must be able to detect particles in all five muon stations within a 25 ns time window around the bunch crossing. Therefore each channel of the system has to be well time aligned with the beam. A first time alignment of the muon system was done using tracks from cosmic particles while the final alignment will be done using particles from the LHC beam. Fig. 5.1 was taken from [34] and shows the time distributions of hits in the five muon stations M1-M5 for backward and forward tracks. The trigger was given by the SPD and HCAL detectors. One can see from Fig. 5.1 that the time alignment of the muon system which has been adjusted for forward tracks (tracks coming from the interaction region) is already quite good. The mean of the hit time distribution varies from approximately $-2$ ns in M1 to 2 ns in M5. The system would be perfectly aligned if the mean hit time would be zero in all five stations.
Table 5.1: Muon system time resolution estimated by analysing 2009 cosmic runs. The values are as expected between 3 and 4 ns.

<table>
<thead>
<tr>
<th>Region</th>
<th>Time resolution [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1R1</td>
<td>4.3 ± 1.2</td>
</tr>
<tr>
<td>M1R2</td>
<td>3.4 ± 0.6</td>
</tr>
<tr>
<td>M1R3</td>
<td>3.7 ± 0.2</td>
</tr>
<tr>
<td>M1R4</td>
<td>3.8 ± 0.2</td>
</tr>
<tr>
<td>M2R1x</td>
<td>3.1 ± 0.3</td>
</tr>
<tr>
<td>M2R1y</td>
<td>3.1 ± 0.3</td>
</tr>
<tr>
<td>M2R2x</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>M2R2y</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>M2R3</td>
<td>3.5 ± 0.2</td>
</tr>
<tr>
<td>M2R4</td>
<td>3.3 ± 0.1</td>
</tr>
<tr>
<td>M3R1x</td>
<td>3.6 ± 0.3</td>
</tr>
<tr>
<td>M3R1y</td>
<td>3.4 ± 0.3</td>
</tr>
<tr>
<td>M3R2x</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>M3R2y</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>M3R3</td>
<td>3.5 ± 0.2</td>
</tr>
<tr>
<td>M3R4</td>
<td>3.1 ± 0.1</td>
</tr>
<tr>
<td>M4R1</td>
<td>4.1 ± 0.4</td>
</tr>
<tr>
<td>M4R2</td>
<td>3.7 ± 0.2</td>
</tr>
<tr>
<td>M4R3</td>
<td>3.7 ± 0.1</td>
</tr>
<tr>
<td>M4R4</td>
<td>3.3 ± 0.2</td>
</tr>
<tr>
<td>M5R1</td>
<td>3.3 ± 0.3</td>
</tr>
<tr>
<td>M5R2</td>
<td>3.5 ± 0.3</td>
</tr>
<tr>
<td>M5R3</td>
<td>3.5 ± 0.1</td>
</tr>
<tr>
<td>M5R4</td>
<td>3.3 ± 0.1</td>
</tr>
</tbody>
</table>

5.1.2 Time resolution

The cosmic runs performed during the commissioning phase were also used to measure the time resolution of the different regions of the muon system. Table 5.1 has been taken from [35] and summarizes the resolution values for all the regions of the system. The estimation shows that the design time resolution of 3 – 4 ns can be achieved.
Figure 5.2: The plots show a comparison between data and Monte Carlo simulations for the muon momentum and transverse momentum. Only muons with $p > 1$ GeV/c and $p_T > 500$ MeV/c have been considered in the analysis. The agreement between offline reconstructed muons and Monte Carlo expectations is very good.

5.2 First collisions

The LHC successfully started again its operation in November 2009. After one year of reconditioning and recommissioning the first circulating beams were established on November 20th leading to first collisions only 3 days later. The particles were accelerated up to 1.18 TeV and with collisions at 2.36 TeV the LHC set a new world record in December 2009. Fig. 5.3 shows a pp-collision at 2.36 TeV recorded by the LHCb experiment on December 14th. Fig. 5.4 shows a di-muon event, where two muons with opposite charge where recorded in the LHCb muon system. A set of data has been taken before the shutdown on December 16th, allowing the LHC experiments to look at the performance of the detectors and to start optimizing parameters.

5.2.1 Comparison Data - Monte Carlo

The data that have been recorded in the muon system during the runs at 450 GeV beam energy at the beginning of December have been analysed and compared with Monte Carlo simulations [36]. Fig. 5.2 shows the muon momentum distribution and the distribution of the transverse momentum as expected by Monte Carlo and as obtained by muon re-
**Figure 5.3:** The plot shows a proton-proton event in the LHCb detector at 2.36 TeV. The proton beams were accelerated up to 1.18 TeV each.

**Figure 5.4:** The plot shows a di-muon event recorded at LHCb. Two muons with opposite charge resulting from a collision were detected. The right plot shows a top and side view of the LHCb muon system for this event.
Figure 5.5: The plots show the efficiency of the muon stations M2-M5 as a function of the muon momentum $p$. The agreement between data and Monte Carlo is rather good. Because of the large amount of material a muon has to pass in order to reach M5, this station starts to become reasonably efficient only for muons with $p > 8 - 10$ GeV/c. The true muons are determined by a selection procedure.

construction. Only long tracks pointing in the muon detector have been selected for the analysis. In addition only muons with a momentum $p > 1$ GeV/c and a transverse momentum $p_T > 500$ MeV/c have been considered. The comparison shows an impressive agreement between offline reconstructed muons and Monte Carlo expectations, indicating a profound understanding of the muon system.

5.2.2 Efficiency

The data acquired at LHCb at 450 GeV beam energy provide a sample of about 6000 reconstructed muon tracks. This statistics is not enough to perform a full alignment of
the detector but can be used to have a first look on the efficiency of the muon system. Fig. 5.5 shows the efficiency of the muon stations M2-M5 as a function of the muon momentum $p$ as obtained by Monte Carlo and from collision data. In order to reach M5 a muon close to the beam pipe must have a momentum of at least $6 \text{ GeV}/c$. At larger polar angles a muon has to pass a larger amount of material and therefore M5 starts to become reasonably efficient for muons with $p > 8 - 10 \text{ GeV}/c$. The true muons are found by selecting only long tracks with $p > 3 \text{ GeV}/c$ that point in the muon detector and are within the detector acceptance. If one can find one hit which can be associated with the track in at least three stations the track is selected as a muon candidate. In a next step a cut on the energy released by the muon in the calorimeter is applied. Furthermore, if there is more than one track resulting from an event the tracks are only selected if they are well separated. Fig. 5.6 shows the efficiency of the five muon stations for muons with $p > 8 \text{ GeV}/c$. The total efficiency for each region of M2-M5 is shown in Table 5.2. In M5 the efficiency is lower than in the other stations. Especially in M5R4 the efficiency is very low due to a softer spectrum of tracks. In M2-M4 the efficiency is everywhere exceeding 99%, except for M2R1 where the timing is not yet well tuned. However, there is clearly more statistics needed in order to determine the efficiency correctly, especially
Table 5.2: Muon system efficiency calculated by analysing first collision data. The efficiency is given by region and by station.

<table>
<thead>
<tr>
<th>Station</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>99.2 ± 0.2</td>
<td>97.5 ± 0.6</td>
<td>99.1 ± 0.3</td>
<td>99.8 ± 0.2</td>
</tr>
<tr>
<td>M3</td>
<td>99.7 ± 0.1</td>
<td>99.4 ± 0.5</td>
<td>99.3 ± 0.2</td>
<td>99.9 ± 0.1</td>
</tr>
<tr>
<td>M4</td>
<td>99.4 ± 0.1</td>
<td>99.4 ± 0.6</td>
<td>98.8 ± 0.3</td>
<td>99.6 ± 0.1</td>
</tr>
<tr>
<td>M5</td>
<td>97.4 ± 0.4</td>
<td>97.2 ± 1.0</td>
<td>98.4 ± 0.3</td>
<td>97.8 ± 0.3</td>
</tr>
</tbody>
</table>

for M1 and for M5 where more high momentum muons are needed. More on the efficiency of the muon system can be found in [37, 38].

5.3 Discussion of results

The time resolution for all regions of the muon system has been determined by analysing cosmics data and has the expected value between 3 and 4 ns. The time alignment from cosmics is very good. In order to refine the timing more statistics from collisions is needed, especially for the inner regions of the system. The agreement between Monte Carlo expectations and reconstructed data is very impressive and indicates the good overall state of the system. The efficiency of the muon system has been estimated using first collision data. The results show an efficiency of ≈ 99 % but there is clearly more statistics needed to determine the efficiency with adequate precision.
Chapter 6

Summary and outlook

A detailed simulation study of the timing properties of the MWPCs of the LHCb muon system has been performed using the drift chamber simulation program GARFIELD. The simulations were done for the final geometry of the muon chambers with a wire spacing of 2 mm, a gap size of 5 mm and a wire diameter of 30 µm. Since nearly all test beam measurements were done with the gas mixture Ar/\text{CO}_2/\text{CF}_4 40/50/10 this mixture has also been used in the simulations.

The simulations have been compared with actual measurements to ensure that the simulation reproduces the measurement well. The good agreement shows that we have a deep understanding of the detector and indicates that the procedure could be used to study other gas mixtures.

The result of the study is a detailed understanding of all the parameters that limit the time resolution of the MWPCs of the muon system. Resolution limiting effects like diffusion, ionization fluctuations, cluster position fluctuations, electronics noise and track position were studied separately to show how they contribute to time resolution. It was shown that ionization fluctuations are one of the major contributions to the time resolution of MWPCs because of the time slewing effect. By applying a double threshold and measuring the rise time of the signal one can correct for the time slewing and improve the time resolution. A time slewing correction for the LHCb muon chambers would lead to a
marginal improvement of 7% and is not needed to fulfill the system requirements.

The influence of the wire pitch on the time resolution was studied separately. Decreasing the wire spacing to 1.5 mm improves the resolution by $\approx 25\%$ but is not desirable because of potential stability problems and higher costs. It was also shown that at a wire pitch of 1.5 mm one reaches a fundamental limit of time resolution of MWPCs operated at 1 bar.

The MWPCs of the LHCb muon system should be operated at the lowest possible threshold. To achieve a time resolution of 3.5 ns and a double gap efficiency of 99\% within a 20 ns time window the threshold can be set up to 10\% of the median signal. This is important to keep in mind to retain the redundancy of the system.

The threshold settings of the past were improved by setting individual thresholds for the 122k front-end (FE) channels of the muon system taking into account the specific properties of each channel. The optimal thresholds were determined by using a method which is based on a centralization and linearization of the noise distribution obtained from the threshold scan and which uses the fundamental frequency $f_0 = 25$ MHz, which is related to the bandwidth of the CARIOCA chip, as a reference point. The method was implemented into a software tool which allows to evaluate the thresholds for the 122k FE channels of the systems within a time of half an hour. The thresholds can be applied directly to the system.

The thresholds have been set to $6 \times$ ENC (Equivalent Noise Charge) in most parts of the system. This corresponds to a threshold of $2 - 10\%$ of the median signal depending on the region which shows that the thresholds are reasonable with respect to the signal heights. The thresholds keep the noise in the muon system to an acceptable level while conserving time resolution and efficiency.

A look at cosmics data and first collision data showed that the LHCb muon system is in a good state. The time resolution has the expected value of $3 - 4$ ns depending on the region. The timing of the muon system is already very good. More statistics is needed to
refine the timing of the inner regions but a timing efficiency well above 95% is definitely reachable. The first results on the efficiency of the muon system are also promising but not very precise due to the lack of statistics.

**Optimization of high voltage settings**

Due to low particle rates ageing doesn’t play a major role in the LHCb muon system in the first phase of operation. Therefore the first step in optimizing the detector is the optimization of the threshold settings in order to achieve the required performance. This has been done by setting minimal electronics thresholds taking into account the noise characteristics of the front-end channels. However, since the LHCb muon system should be operated for 10 years at high particle rates without significant ageing, it is of particular importance to operate the detector not only at the lowest possible threshold but also at the lowest possible high voltage (HV).

In order to find the appropriate HV settings one can proceed as described in the following. One can think of the threshold not only in units of for example fC but also in units of primary electrons (p.e.) defined as the peak of a pulse created by a single ionization electron. It has been determined that the optimal threshold for the MWPCs of the muon system is about 4–6 p.e. [21] which means, since we have about 100 ionization electrons per cm, losing 4–6% of the total ionization. After one has defined the minimal threshold in fC or electrons as described in chapter 4 one can estimate the gas gain such that this threshold corresponds to for example 4 p.e.. Knowing the minimal gas gain needed one can evaluate the HV by using Diethorn’s formula (Eq. 3.15). Fig. 6.1 shows the correlation between gas gain and HV for a M2R4 chamber. In this case a threshold of 9 fC corresponds to 4 p.e. at a HV of 2.6 kV (G ≈ 7 × 10^4). After determining the minimal HV one has to ensure that the required efficiency is reached otherwise the gas gain has to be raised. Finally, the voltage has to be tuned in order to correct for temperature and pressure variations within the system that influence the gas gain. More on optimization of the high voltage settings can be found in [21].
Figure 6.1: The plot shows the correlation between gas gain and HV as given by Diethorn’s formula for a M2R4 chamber. A threshold of 9 fC corresponds to 4 p.e. at a HV of 2.6 kV ($G \approx 7 \times 10^4$).

At the moment the detector is operated at a HV of 2.65 kV where we expect an efficiency well above 99%. The gas gain at this operating point is approximately $10^5$. The goal is to lower the HV and to reach a gas gain of $\approx 5 \times 10^4$. 
Bibliography


