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Crosstalk, Cathode Structure and Electrical Parameters of the MWPCs for the LHCb Muon System

Werner Riegler
CERN

Abstract

This note discusses the electrical characteristics of the Multi Wire Proportional Chambers (MWPCs) for the LHCb muon system that were originally developed at PNPI [1]. Optimized layouts for cathode structure and readout traces together with the expected crosstalk numbers are presented. We conclude that cathode pad dimensions should not be smaller than 3 cm in order to limit the cluster size to ≤ 1.2. We also conclude that a front-end electronics input resistance of $\leq 50\,\Omega$ is preferred in order to limit the capacitive crosstalk. In some regions a resistance of $100\,\Omega$ might be acceptable. In order to limit the crosstalk for chambers with a 'chessboard' cathode structure it is essential that we run the signal traces parallel to the wires.

Contents

Chapter 1

Introduction

The general chamber characteristics of MWPCs are discussed in detail in [2]. In this note we want to concentrate on the electrical characteristics and the crosstalk of the actual geometry that we intend to use in LHCb. Although the basic chamber geometry is the same for all the regions, the actual electrical characteristics of the chambers vary a lot in different regions and stations since the readout elements are very different.

In R4 the wire signals are read out (Fig. 8.1), i.e. we read a negative signal from the anode wires which is AC coupled to the amplifier (we need the HV blocking capacitor). The cathode is unsegmented and on ground potential. The detector capacitance is very high (up to 250pF). Since the mutual capacitance between two wire pads is very small, crosstalk is not a big issue.

In R3 the wires are grounded (at AC) and we read the cathode pads (Fig. 8.2). The signal is positive and has half the size of the anode wire signal. There are two cathode pads 'under' the wire pad. Crosstalk is an important issue in this geometry and has to be studies carefully. The cathode pads are accessible from the side, therefore the readout is easy.

In R1,R2 of M4,M5 we read a 2D array of cathode pads (Fig. 8.3). The wires are again grounded at AC and capacitive coupling between pads is again an issue. In addition we have to bring the signals from the central pads to the edge of the chamber which causes additional crosstalk that has to be watched.

In R1,R2 of M2,M3 we read a 2D array of cathode pads and in addition the signals from the wires (Fig. 8.5). In addition to all the above problems we introduce a resistance between wires and ground (from the amplifier that reads the wire) which adds another complication.

This note presents a detailed study of all the electrical issues of the different geometries. The chamber signal simulations where done with GARFIELD, the detector capacitances where calculated with MAXWELL, the crosstalk signals were finally studied with PSPICE.

Chapter 2

General Description

The dimensions of the electrodes and signal lines are small compared to the preamp peaking time. Therefore we study the chamber not as a transmission line but as a quasi-static circuit. The voltage drop due to inductances is quite small, that's why the capacitance matrix of the chamber contains all the relevant information.

The electrical characteristics of a static multi-electrode system are given by

$$Q_i = \sum_{j=1}^{n} c_{ij} V_j \tag{2.1}$$

where Q_i and V_i are the charge and the voltage on electrode i. The Capacitance Matrix c_{ij} is symmetric and just depends on the chamber geometry. The actual mutual capacitances between the electrodes are given by

$$C_{ij} = -c_{ij} \quad i \neq j \qquad C_{ii} = \sum_{j=1}^{n} c_{ij} \tag{2.2}$$

The electrical circuit representing the electrode system is given in Figure 2.1. For the MWPC studies the capacitance matrix was calculated with the MAXWELL 2D extractor [3].

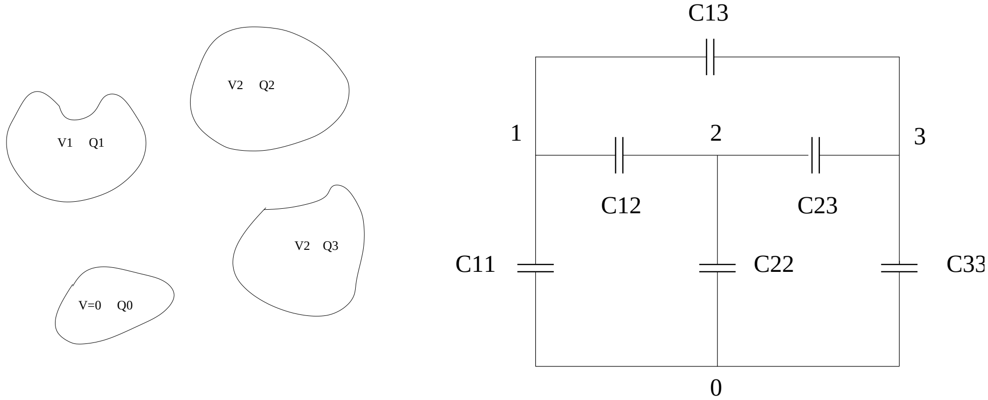

Figure 2.1 *: A general electrode system together with it's equivalent electrical circuit.*

Chapter 3

HV Issues

The HV loading resistor and the HV blocking capacitor have to be chosen according to our requirements. Since they have an important impact on the electrical chamber characteristics we will discuss their choice in detail.

A MIP deposits an average of 100 electrons in the two chamber gaps (1cm track length, $Ar/CO_2/CF_4$ 40/50/10). Assuming a gas gain of 2×10^5, a factor 2 for the fact that the background consists mostly of electrons and a rate of 1 MHz per pad we find a current of 6.4 μA that has to be supplied by the HV module.

3.1 HV Loading Resistor

The upper bound on the HV loading resistor is given by the maximum voltage drop that we allow. If we want a drop of less that 1 V the maximum for R_L is 156 kΩ.
The lower bound is given by the fact that R_L is a parallel noise source i.e. it contributes to the ENC as

$$ENC = \sqrt{\frac{4kT}{R_L}} \tag{3.1}$$

For R_L >10 kΩ the contribution to the total detector ENC is negligible. Also the signal fraction 'leaving' the system through the HV resistor becomes negligible since for a typical preamp input impedance of $< 100\,\Omega$ the signal sharing is 1%.

3.2 HV Blocking Capacitor

The upper bound on the value of the blocking capacitor is given by the maximum allowed energy stored in the capacitor. In case of spark that totally discharges the wire pad there are two effects that can destroy the chamber. The high current can heat up the wire and make it break. The spark pulse also produces a very high current into the preamp which might me destroyed. At 3.5 kV, a total capacitance of 1 nF is assumed to be an upper limit in order to avoid problems like that.

The charge deposited on the wire has to be fed back from the HV supply. This happens with a time constant of $R_L C$ which evaluates e.g to 100 μs for C=1 nF and R_L=100 kΩ. During that time we have a total charge deposit of $6.4\,\mu A \times 100\,\mu s = 640$ pC. This charge deposit creates a voltage drop of $\Delta V = Q/C = 0.64$ V. Since the charge deposit fluctuates the voltage will fluctuate around this value. We see that this voltage drop also depends on the loading resistor, the dependence on the capacitor cancels out.

A lower limit is set by requirements on charge collection efficiency. Fig. 3.1 shows a simplified schematic of a wire pad chamber. The induced current i and the current seen by the preamp i_1 are simply related by

$$\frac{i_1}{i} = \frac{1}{1 + \frac{C_{det}}{C} + sC_{det}R} \tag{3.2}$$

The circuit represents a simple integrator. We see that for $R = 0$ the current divides according to the detector and decoupling capacitances, so increasing the decoupling capacitor also increases i_1, however only as long as C/C_{det} is larger than sRC_{det}. Fig. 3.1 shows that the input resistance limits the pulse-hight so there is also a maximum useful value for the blocking capacitor.

The useful number is not the absolute pulse-height but the signal/noise ratio. If the shape if the amplifier delta response does not change too much with the different values on the input, the noise scales in the same way as the signal, so the signal to noise ratio is not affected. It is however still desirable to collect a large amount of charge.

Another restriction on the decoupling capacitor is set by the crosstalk effects that will be discussed later. For now we assume R_L=100 kΩ and C=1 nF to be a good baseline choice for all detector types.

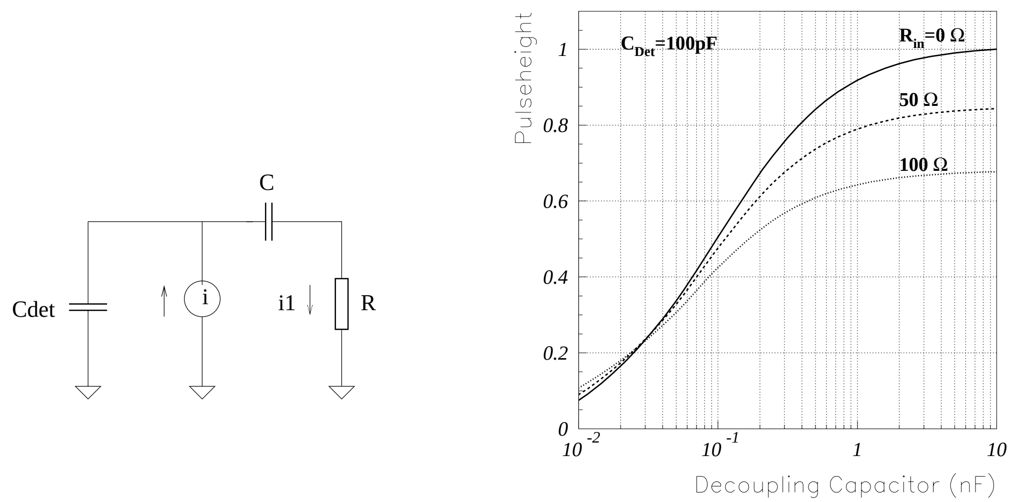

Figure 3.1 *: The left figure shows a simplified schematic of a wire pad. The right figure shows the pulse-height for different input resistances and decoupling capacitors.*

Chapter 4

Crosstalk Specifications

When a particle crosses a pad we find three main mechanisms that make the neighbouring pad fire:

- Direct induction when a particle crosses between two pads or close to the edge of a pad.
- Capacitive coupling when the signal couples to a neighbouring pad due to it's mutual capacitance.
- 'OR'ing of two pads in two gas gaps for a track that is not perpendicular to the pads.

First we have to define and specify our crosstalk requirements. We define the **signal fraction between Pad1 and Pad2** as the ratio of the pulse-heights between Pad2 and Pad1 where the particle is crossing.
We define the **crosstalk between Pad1 and Pad2** as the probability that this Pad2 is firing when a particle is crossing Pad1. This number depends of course on the threshold and the signal fraction.
We define the **cluster size** as the average number of strips fired for a single track. Figure 4.1 shows the pulse-height distribution for a double gap chamber in units of ionization electrons i.e. peaks of a single ionization electron. We find an average pulse-height of about 60 e-. With this histogram we can calculate the crosstalk from the pulse-height fraction by simply drawing numbers from the pulse-height histogram, multiplying with the crosstalk fraction and looking if the crosstalk signal is above threshold. The result is shown in Figure 4.1. At our working point we have a threshold of 3-6 electrons, so if we want a crosstalk of $< 5\,\%$ we can allow a signal fraction of $< 2\,\%$. Taking into account the fact that the background particle signals are higher than the muon signals we would be more comfortable with a pulse-height fraction of $1\,\%$.

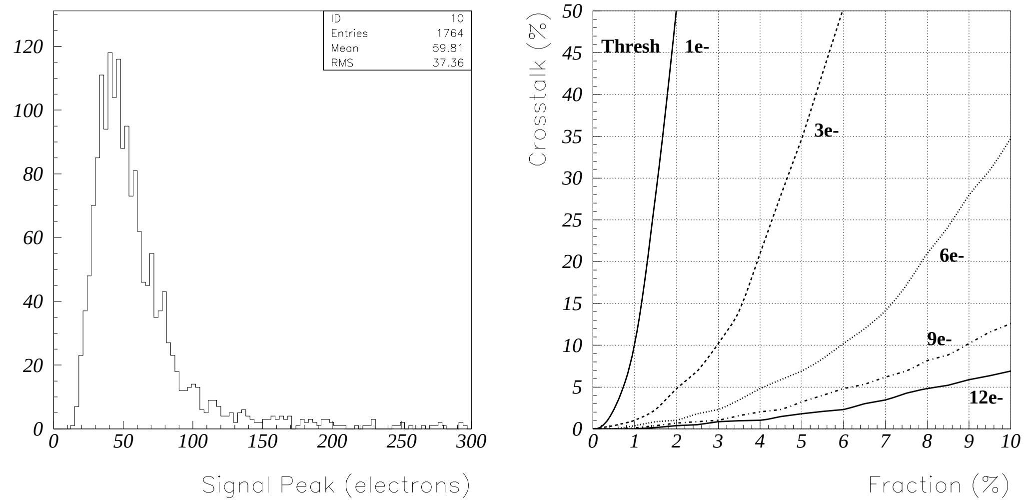

Figure 4.1 *: The left figure shows the pulse-height distribution for a double gap chamber. The particles crossing the chamber are 10 GeV muons. Since most of the background particles are electrons we have to assume a pulse-height distribution that is a factor 2 higher. The right figure shows the expected crosstalk for a given pulse-height fraction. Usually the noise at a gas gain of* 1×10^5 *allows a threshold of 3-6 electrons.*

So we can finally write our specification

If a particle crosses a pad, the pulse-height on the neighbouring pad should be $< 1 - 2\,\%$ of the pulse-height of the signal pad.

Chapter 5

Directly induced Crosstalk

If a particle is passing the chamber, perpendicular to the wire plane and close to the boarder of two pads, the avalanches on the wires induces a signal on both pads. The total induced charge on a cathode pad versus distance of the track from the boarder is shown in Figure 5.1 (5 mm gap, 1.5 mm wire pitch). The figure also shows the crosstalk that can be calculated from the figures in the previous chapter.

By integrating the probability distribution the cluster size is calculated to be

$$1+\frac{8.36}{w} \qquad 1+\frac{6}{w} \qquad 1+\frac{4.42}{w} \qquad \text{for threshold of} \qquad 1e- \quad 3e- \quad 6e- \tag{5.1}$$

where w is the width of the pad in mm and $w > 10$ mm. So for a pad of 1 cm width and a threshold of 3e- we find a cluster size of 1.6. If we want to keep the cluster size < 1.2 the smallest cathode pad dimension has to be $> 3\,cm$. This limit is set simply by the gap size of 5 mm.

Before discussing the efficiency as a function of the distance from the pad boarder we have to specify the gap between the cathode pads. In order to avoid charge-up problems, the distance between cathode pads should not exceed 0.4 mm. Since we want to minimize the capacitive coupling between pads we have to introduce a ground strip between the cathode pads.

The upper limit on the width of this strip is given by the fact that we don't want to get inefficiency at the border of two gaps. To estimate this inefficiency we use some experimental data [4]. We normalize the average pulse-height at the working point (3.15 kV) to 1 and define the time window at this operating point. Then we look for the efficiency at lower gas gain in this time window. The efficiency versus pulse-height fraction is shown in Figure 5.2. At a pulse-height of 50% i.e. for a track between two pads we find an efficiency of 97% in a 20 ns time window. From this we can calculate the efficiency as a function of the distance from the border which is also shown in Figure 5.2.

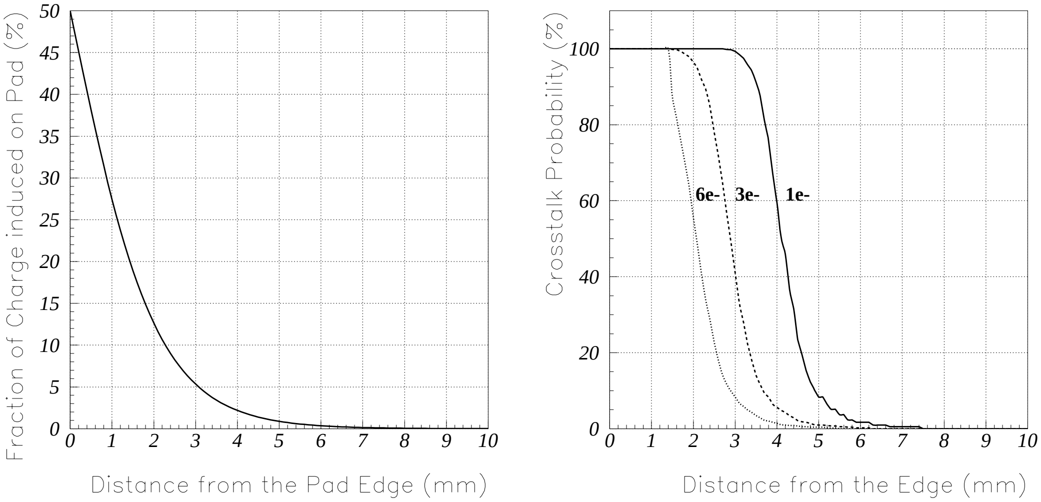

Figure 5.1 *: The left plot shows the fraction of charge induced on one pad if the track passes the chamber perpendicular to the wire plane at a given distance from the edge of the pad. At a distance of 5 mm the fraction is about 1% for a threshold of 3e-. The right figure shows the corresponding crosstalk probability.*

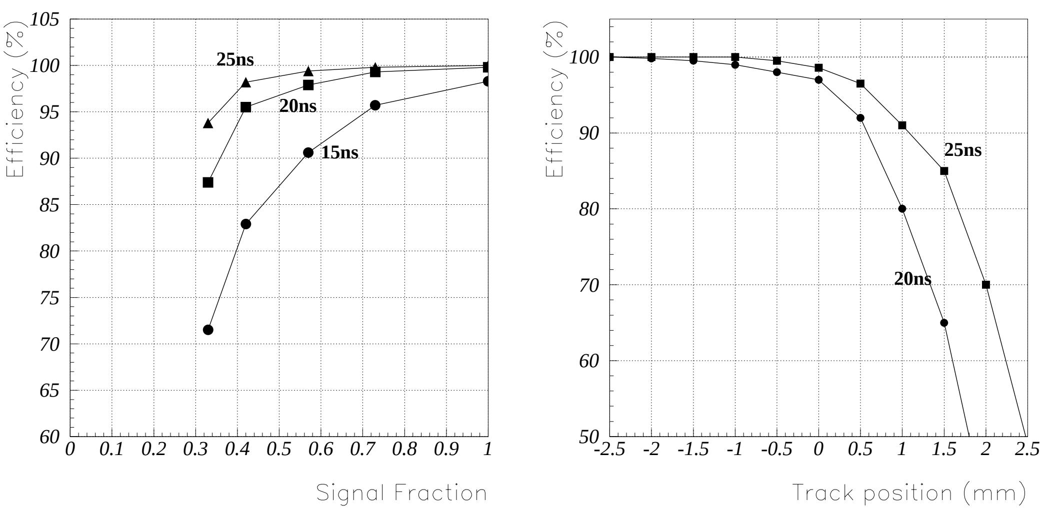

Figure 5.2 *: The left plot shows the efficiency as a function of pulse-height compared to the pulse-height at the working point. The right plot finally shows the efficiency as a function of distance of the track from the pad edge.*

In case there is no gap between two neighbouring pads we find and efficiency of 98.5(97)% for a 25(20) ns gate. In case we have a gap of 1.3 mm we find an minimum efficiency of 95(88)% for a 25(20) ns time window. We should therefore not exceed this pad-pad distance of 1.3 mm i.e. 0.5 mm guard strip plus 0.4 mm gaps.

These numbers are however very pessimistic. They are only true if the wire pitch is very small compared to the dimensions we are talking about. This is however not true since the wire pitch is 1.5 mm. Also, the tracks are not perpendicular to the chamber which also reduces the efficiency loss. On top of that it is planned to use two independent chambers for each station, therefore the above problem will be less severe.

Chapter 6

Capacitances

The mutual capacitances between all the electrodes in the chamber were calculated with MAXWELL. The chamber geometry is shown in Figure 6.1. In all the scenarios the SignalLine, SignalGuards and SignalGap are 0.25 mm. The G10 board was assumed to have $\epsilon = 4.4$.

The Wire-Pad to Wire-Pad capacitance is dominated by the first few wires at the boarder of the pad. The mutual capacitances between individual wires are given in table 6.1. Since the smallest wire pads that we want to use have 4 wires we can assume the same mutual capacitance of 5.4 pF/m for all wire pads. This number will however underestimate the coupling since the wires are fixed on a bar at the end of the chamber. This bar has high ϵ, so although the total overlap is only of the order of 1 cm on each side, the ends will contribute to the capacitance. To estimate the effect we put a row of wires on top of a G10 bar ($\epsilon = 4.4$) and simulate the numbers with MAXWELL. The result is a factor two higher than the values for the gas volume. Finally the Pad-Pad capacitance is given in (Fig. 6.2). If the wire pads consist of only a few wires, the directly induced crosstalk to neighbouring wires will decrease the capacitive crosstalk [2].

The capacitance of the wire pad to ground is given by $2 \times 0.475 \times A(cm^2)$ pF where A is the wire pad area. This is however only the capacitance in the gas volume. The additional capacitance to ground due to the chamber end depends strongly on the chamber design. Experience shows that the effect is significant.

To discuss the CathodePad-CathodePad capacitances we go through the individual columns in Table 6.2. The geometry is given in Figure 6.1. All numbers are quoted for a double gap chamber.

Table 6.1: Mutual wire capacitances in the gas volume. The capacitance on the wire bar is a factor 2 higher.

Wire	mutual cap (pF/m)	wires/pad	total Pad-Pad cap (pF/m)
1-2	3.044	1	3.044
1-3	0.78	2	4.774
1-4	0.17	3	5.209
1-5	0.042	4	5.321
1-6	0.011	5	5.35
1-7	0.0028	6	5.35
1-8	0.0007	7	5.35
1-9	0.00021	8	5.35

Table 6.2: Mutual capacitances for different detector geometries.

Column	1	2	3	4	5
Pad Guard (mm)	-	1	1	0.5	0.5
Pad Gap (mm)	0.4	0.4	0.4	0.4	0.4
G10 thickness (mm)	1.6	1.6	0.8	1.6	1.6
Pad-Pad (pF/cm)	1	0.23	0.151	0.342	0.192
Pad-TopPadGuard (pF/cm)	-	0.77	0.72	0.67	0.56
Pad-SignalLine (pF/cm)	-	0.37	0.56	0.37	-
SignalLine-SignalGuard (pF/cm)	-	0.96	0.82	0.95	-
Pad-SignalGuard (pF/cm)	-	1.10	1.55	1.10	-
Pad-BottomPadGuard (pF/cm)	-	-	-	-	0.403
Pad-Wires (pF/cm^2)	0.475	0.475	0.475	0.475	0.475
Wires-SignalGnd (pF/cm^2)	0.475	0.475	0.475	0.475	0.475
Pad-SignalGnd (pF/cm^2)	0.115	0.115	0.115	0.115	0.115

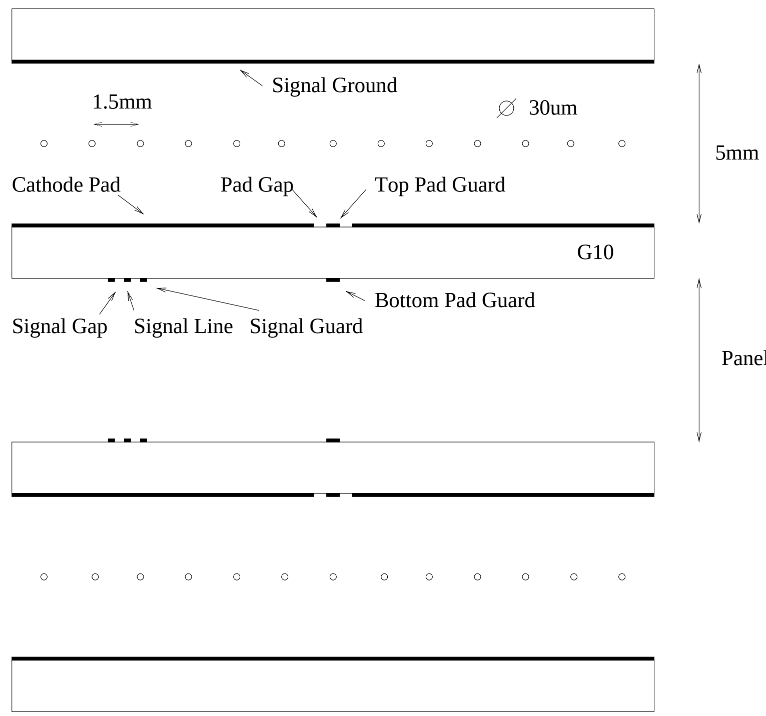

Figure 6.1 : *General detector geometry. The electrodes in the two gaps are ORed together. Only in Region 1 and Region 2 we need the signal line on the bottom of the board in order to read the signals from the 'chessboard' cathode pad structure..*

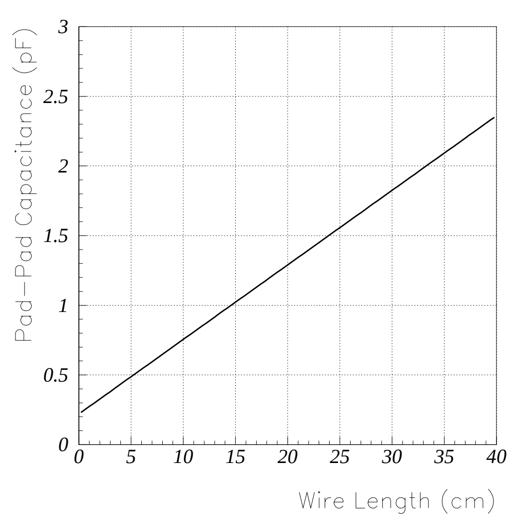

Figure 6.2 : *Wire pad capacitance versus wire length. The offset at zero length is due to the 1 cm overlap on both wire fixation bars.*

The first column shows the values for a geometry with pad distance 0.4 mm, a 1.6 mm G10 board and no guard strip. We find a pad-pad capacitance of 1 pF/cm which is too high. To reduce this capacitance one can increase the pad-pad distance, but in that case one has to put a ground strip in between in order to avoid charge-up problems.

The second column shows that a 1 mm guard strip (only on the top side) decreases the coupling from 1 to 0.23 pF/cm. By reducing the board thickness to 0.8 mm we find a decrease to 0.151 pF/m (column 3), but this has disadvantages for reading out the 'chessboard' geometry since the coupling of the SignalLine to the pad becomes too high.

With a guard of 1 mm we might already run into problems with inefficiencies, so we choose a guard of 0.5 mm which is shown in column 4. The pad-pad capacitance is 0.345 pF/cm. We can still reduce this number by putting a guard strip also on the bottom of the board. Column 5 shows that we arrive at a capacitance of 0.192 pF/cm. It will of course increase the total pad-ground capacitance.

In some regions of the muon system we have to read the signals from a 'chessboard' geometry of cathode pads (Fig. 8.3). Running the signal traces on the bottom of the board requires special attention. The mutual capacitance between the signal trace and the cathode pads causes large crosstalk. Shielding of this trace introduces however additional pad-ground capacitance. In order to avoid an expensive multilayer board we use a signal line with two grounded guard lines. The table shows the capacitances for a 0.25 mm SignalLine with two 0.25 mm SignalGuards at a distance of 0.25 mm. We prefer the 1.6 mm board since the SignalLine-Pad Capacitance reduces from 0.56 to 0.37 pF/cm.

The line for reading the signal has a characteristic impedance of 38 Ω, 1.37 pF/cm to ground and 2 nH/cm. The propagation time is 19 cm/ns. For a line of 50 cm this gives an input time constant of $\sqrt{LC}$=3.7 ns which should be acceptable.

Chapter 7

Crosstalk Sources

In the following we will discuss all the different sources of crosstalk. We assume an amplifier with transfer function and delta response of

$$g(s) = \frac{n!\tau}{(1+s\tau)^{n+1}} \qquad \rightarrow \qquad f(t) = \left(\frac{t}{\tau}\right)^n e^{-\frac{t}{\tau}} \qquad t_p = n\tau \tag{7.1}$$

We assume a peaking time of $t_p = 10\,\mathrm{ns}$ and $n = 3$. The transfer function is flat out to a certain frequency and then cuts off. Normalizing the flat part to 1 we find the function to have the value of p at a frequency given by

$$f = \frac{1}{2\pi\tau}\sqrt{\frac{1}{p}^{\frac{2}{n+1}} - 1} \tag{7.2}$$

so for $t_p = 10\,\mathrm{ns}$ and n=3 the transfer function reaches a value of p=0.99,0.5,0.01 at frequencies 3.4, 30.7, 143 MHz. If we study the effect of capacitances we will assume that the transfer function drops to 50% at a frequency of f=30 MHz i.e. we will approximate a capacitor C by a resistor with value 1/(2π f C).

For the following discussion we assume a wire pitch of 1.5 mm, cathode-wire distance of 2.5 mm, wire diameter 30 μm. Since the dimensions of the chambers are short with respect to the signal propagation time we study the crosstalk with a quasistatic model, i.e. the crosstalk is given by capacitive coupling only.

The induced current signal is assumed to have a $1/(t+t_0)$ shape with a t_0 of 3 ns.

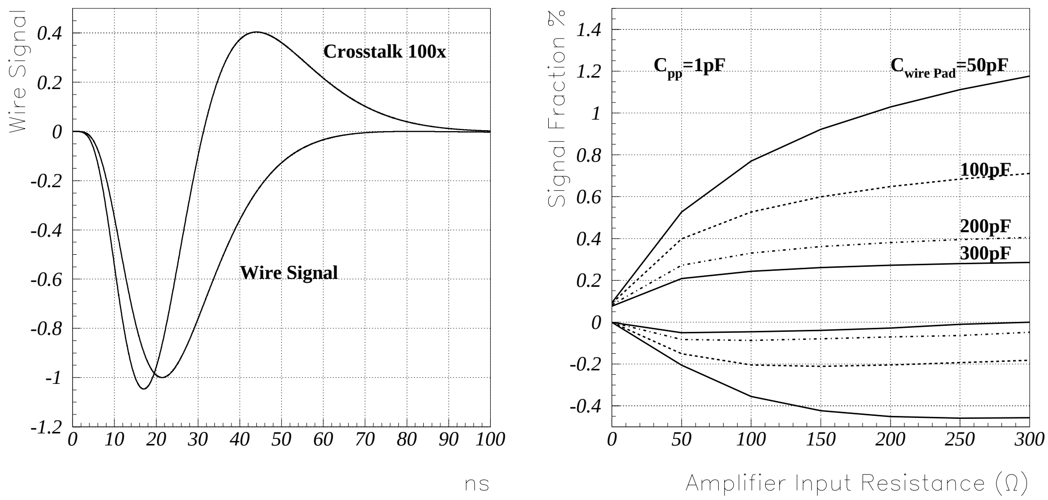

Figure 7.1 *: The left figure shows a wire pad signal together with the crosstalk signal on the neighbouring wire pad. The crosstalk signal has the same polarity. The right figure shows the crosstalk for different wire pad capacitances for C_{pp}=1pF. The crosstalk scales with C_{pp} i.e. for C_{pp}=2 pF all the numbers have to be multiplied by 2. The negative lines show the peak of the overshoot.*

7.1 Wire-Pad to Wire-Pad Crosstalk

The simplest chambers consist of a set of wire pads. We assume a row of wires between two grounded planes. Several wires are ORed together to form on wire pad. The dominating coupling between the pads is given by the Pad-Pad Capacitance C_{pp}. The equivalent circuit is shown in Fig. 7.2.

The approximate analytical formula for the circuit is given by

$$\frac{i_2}{i_1} \approx \frac{sRC_{pp}}{1 + 2sRC_{wp}} \tag{7.3}$$

where R is the preamp input resistance, and C_{wp} is the mutual capacitance between the wire pad and one cathode pad. So we find

$$i_{cross} \approx sRC_{pp} \quad \text{for} \quad RC_{wp} << 2.5ns \qquad \text{and} \qquad i_{cross} = \frac{C_{pp}}{2C_{wp}} \quad \text{for} \quad RC_{wp} >> 2.5ns \tag{7.4}$$

Figure 7.1 shows a wire pad signal together with the crosstalk signal on the neighbouring pad.

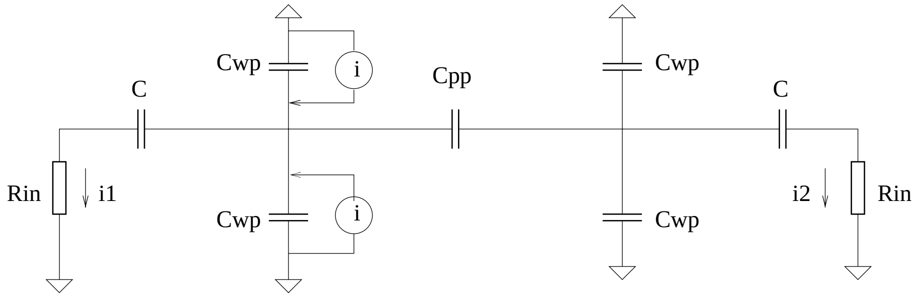

Figure 7.2 *: Equivalent circuit showing the wire pad crosstalk. First, the current divides between the resistances $R_{in} + 1/sC$ and $1/sC_{pp}$ which approximately evaluates to $R_{in} + 5\,\Omega$ and $5.3\,k\Omega$. The current passing through C_{pp} splits between $1/2sC_{wp}$ and $R_{in} + 1/sC$.*

The Maxwell calculation gives a Pad-Pad capacitance of 2.6 pF/m which gives about 1 pF for the largest wire pads.

If a particle passes the chamber between two wire pads we of course find a signal on both pads. This probability is 1.5 mm/width of the wire pad. For a 5 cm Wire Pad this evaluates to 3 %. This kind of crosstalk is of course inevitable.

7.2 Cathode-Pad to Cathode-Pad Crosstalk

The cathode pad crosstalk has two dominant sources: crosstalk through the wire pad for cathode pads that are sitting under the same wire pad, and crosstalk through the mutual pad-pad capacitance for all pads. The equivalent circuits are shown on Figure 7.3 and 7.4.

7.2.1 Crosstalk along the Wire

To study this effect we set $C_{pp} = 0$. At a frequency of 30 MHz the capacitor $C_{wp} = 75\,pF$ represents a resistance of $70\,\Omega$ while the decoupling Capacitor C=1 nF represents a resistance of $5\,\Omega$. Since this resistance is in series with the preamp input resistance we immediately see that the cathode pad amplifier resistance has a much smaller influence on this crosstalk than the anode amplifier input resistance. The crosstalk current is given by

$$\frac{i_2}{i_1} \approx -\frac{2(1+sRC)}{(1+sRC) + (\frac{C}{C_{wp}} + sR_{in}C)(1 + \frac{C_{wp}}{C} + sRC_{wp})} \tag{7.5}$$

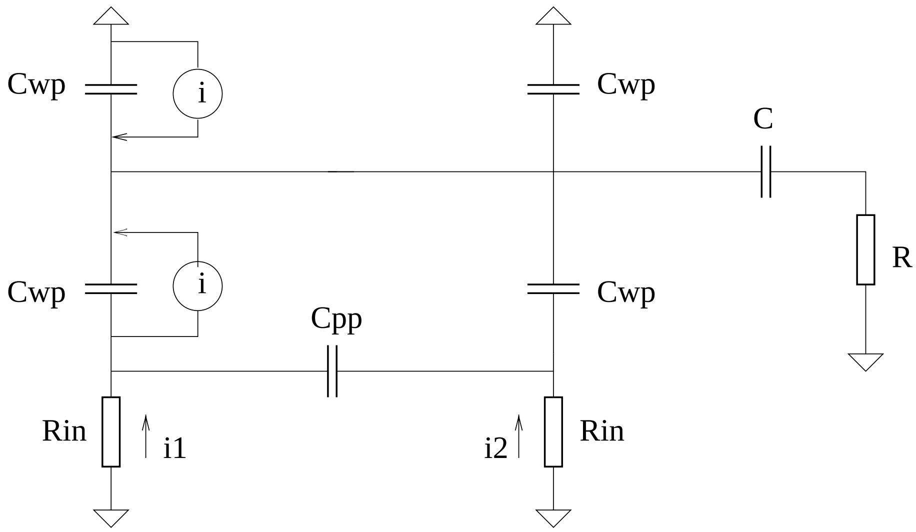

Figure 7.3 *: Approximate equivalent circuit for two neighbouring cathode pads under the same wire pad.*

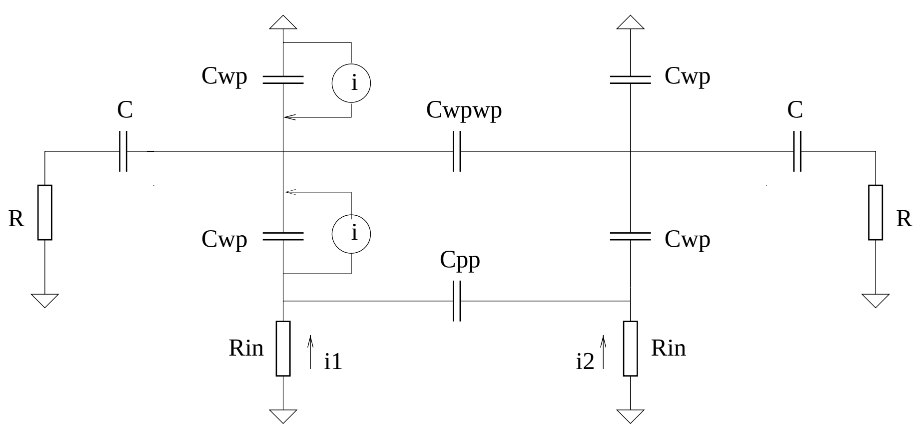

Figure 7.4 *: Approximate equivalent circuit for two cathode pads sitting next to each other and NOT under the same wire pad. Since the wire-pad wire-pad capacitance is very small, only the direct capacitive crosstalk through* C_{pp} *is significant.*

where R is the wire amplifier input resistance, R_{in} is the cathode amplifier input resistance, C the decoupling capacitor and C_{wp} is the mutual capacitance between wire pad and one cathode. In order to distinguish the different sources we first assume the amplifier input resistance to be zero. In that case we find

$$\frac{i_2}{i_1} \approx -\frac{2C_{wp}}{C} \tag{7.6}$$

so the current divides between the wire-pad capacitance and the decoupling capacitor. For a typical wire pad impedance of 75 pF we find a crosstalk of 15%. Since this result is independent of the frequency the crosstalk signal has the same shape but opposite polarity. Since we only discriminate positive signals we don't get a crosstalk hit. However it will cause baseline fluctuations if the rates are high which will cause loss of time resolution. We can reduce this effect by reducing C_{wp} i.e. by grouping less wires into one wire pad. Increasing the decoupling capacitor C is not comfortable as discussed earlier.

In some regions of the detector we do not read the wire signals, so we can ground the wires at AC (R=0) and get

$$\frac{i_2}{i_1} \approx -\frac{2}{1 + (1 + \frac{C_{wp}}{C})(\frac{C_{wp}}{C} + sRC_{wp})} \tag{7.7}$$

This is the transfer function of a simple integration stage which will change the shape of the pulse but will not create a positive overshoot that would cause a crosstalk hit.

If however we want to read the wires, the wire amplifier impedance causes a positive overshoot. To see this effect we set $R_{in} = 0$ and get

$$\frac{i_2}{i_1} \approx -\frac{2(1 + sRC)}{(1 + sRC) + \frac{C}{C_{wp}}(1 + \frac{C_{wp}}{C} + sRC_{wp})} \tag{7.8}$$

The s in the numerator indicates signal differentiation which causes the positive overshoot of the signal. For this effect we have to use a full Pspice model.

Fig. 7.5 shows a cathode pad signal together with with the crosstalk signal on the neighbouring pad. This effect is quite large. The wires have a mutual capacitance of $0.475\,\text{pF}/cm^2$ to the cathode, so if we want a crosstalk of $< 1\%$, the overlap area between

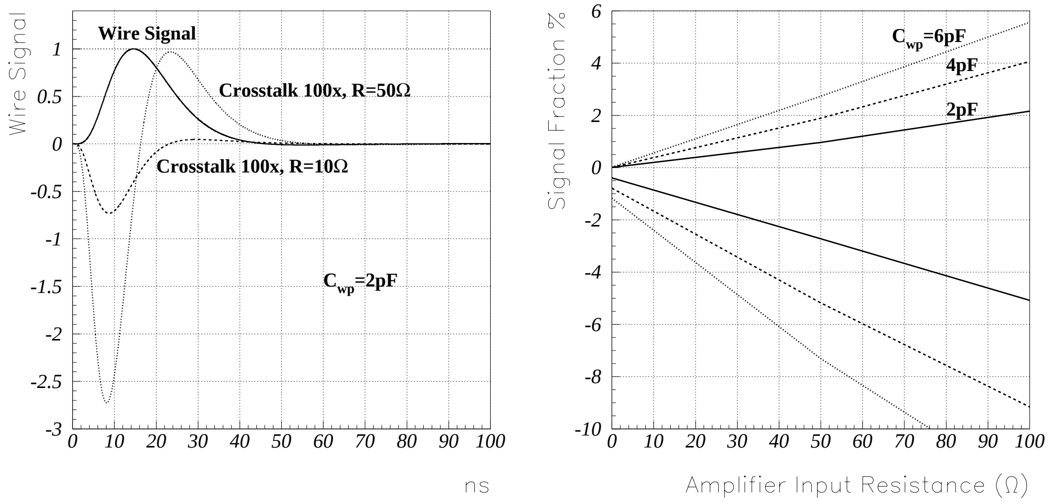

***Figure 7.5** : The left figure shows the cathode pad signal together with the crosstalk for 2 different wire amplifier resistances. The effect is quite prominent. The right figure shows the crosstalk for different mutual wire to pad capacitances. Note that the crosstalk due to direct capacitive pad-pad coupling is neglected here.*

a cathode pad and the wire pad has to be $< 5(2)\,\mathrm{cm}^2$ for R_{in} of $50(100)\,\Omega$. We see that only for very small wire-pad cathode-pad overlap we are able to read the wire signals in addition to the cathode signals.

7.2.2 Crosstalk through the mutual Pad-Pad Capacitance

To separate this effect from the crosstalk along the wire we ground the wires and set the decoupling capacitor to a very high value. This crosstalk has again same sign as the cathode pad signal.

In this case the crosstalk is given by

$$\frac{i_2}{i_1} = \frac{sR_{in}C_{pp}}{1 + sR_{in}C_{wp}} \tag{7.9}$$

where R_{in} is the cathode pad amplifier input resistance. So we find

$$\frac{i_2}{i_1} \approx sR_{in}C_{pp} \quad \text{for} \quad R_{in}C_{wp} << 5ns \tag{7.10}$$

and

$$\frac{i_2}{i_1} = \frac{C_{pp}}{C_{wp}} \quad \text{for} \quad R_{in}C_{wp} >> 5ns \tag{7.11}$$

The same behaviour we already found for the wire pad chamber, so the signal characteristics are same as shown in Fig. 7.1.

For neighbouring cathode pads under the same wire this effect partly cancels with the negative crosstalk as shown before. This effect will be useful when we read the signals along traces that run on the bottom of the cathode panel.

7.3 Results

So we can finally conclude on the crosstalk mechanisms

- The Wire-Pad to Wire-Pad crosstalk has the same polarity as the wire pad signal. It scales with the Pad-Pad capacitance. The crosstalk is smaller for large wire pads. Since the Pad-Pad capacitance is small (0.054 pF/cm) the crosstalk is not a big issue.
- The Cathode-Pad to Cathode-Pad crosstalk through the wire is quite dramatic if the wires are not grounded. It has opposite polarity but still crosses the threshold because of signal differentiation. The mutual cathode to wire capacitance has to be smaller than 2.4(1) pF for R_{in}=50(100) Ω.
- The direct Cathode-Pad to Cathode-Pad crosstalk has the same polarity and scales with the mutual Pad-Pad capacitance. It is smaller for large C_{wp}.
- Since the crosstalk along the wire has opposite polarity compared to the direct capacitive crosstalk, the two effects cancel partly. We can take advantage of this effect when we have to read the signals from a 'chessboard' structure of cathode pads.

Chapter 8

The Muon System

Finally we want to calculate the crosstalk of the individual chambers. The physical channel sizes are given in table 8.1. For details see [5]. For the crosstalk calculations we use the following electrode arrangements: 1.6 mm G10 board, 0.4 mm PadGap, 0.5 mm PadGuard (top and bottom). For 'chessboard pads': 0.25 mm SignalLine, 2×0.25 mm SignalGuard at distance 0.25 mm.

Table 8.1: Muon System Parameters. The units are cm. W indicates the wire pad, C indicates the cathode pad. The pad sizes are given in cm. E.g. C:3.75,3.1 (8,8) indicates a cathode pad with 3.75 cm in X and 3.1 cm in Y, there are 8 pads in X and 8 pads in Y for one chamber. The (,) numbers indicate how many of the physical pads are ORed into one logical pad.

	M1	M2	M3	M4	M5
R1		C: 3.75,3.1(8x8) W:0.63,25 (48x1) C(1,1) W(1,1)	C:4.05,3.4(8x8) W:0.67,27(48x1) C(1,1) W(1,1)	C:2.9,3.6(12x8) C(1,1)	C:3.1,3.9(12x8) C(1,1)
R2		C:7.5,3.15(8x8) W:1.25,25(48x1) C(1,2) W(1,1)	C:8,3.35(8x8) W:1.35,27(48x1) C(1,2) W(1,1)	C:5.8,7.3(12x8) C(1,1)	C:6.2,7.7(12x8) C(1,1)
R3	C: 2,5(48x4) C(2,2)	C:2.5,12.5(24x2) C(1,1)	C:2.7,13.5(48x2) C(1,1)	C:5.8,14.5(24x2) C(2,1)	C:6.2,15.5(24x2) C(2,1)
R4	W: 2,20(192x1) W(4,1)	W:5,25 (48x1) W(1,1)	W:5.4,27(48x1) W(1,1)	W:5.8,29(48x1) W(4,1)	6.3,30.9(48x1) W(4,1)

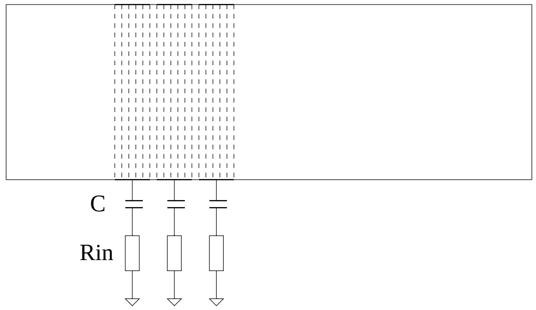

Figure 8.1 *: In R4 we simply connect a certain number of wires into wire pads.*

Table 8.2: R4 crosstalk numbers. The crosstalk is given in % and is quoted for input resistances of 50, 100 and 200 Ω. C_{pp} is the pad-pad capacitance. C_{pg} is the pad-ground capacitance.

Station	$C_{pp}(pF)$	$C_{pg}(pF)$	50 Ω	100 Ω	200 Ω
M1	1.29	38	0.74	1.13	1.6
M2	1.56	119	0.6	0.734	0.9
M3	1.66	139	0.55	0.7	0.83
M4	1.77	160	0.55	0.681	0.801
M5	1.86	182	0.535	0.65	0.76

8.1 Region 4

In R4 we use wire pad chambers (Fig. 8.1). The mutual capacitance between wire pad and one cathode is given by

$$C_{wp} = 0.475 \times A(cm^2)\, pF \tag{8.1}$$

The total capacitance to ground is twice this value. The mutual pad-pad capacitance is given by

$$C_{pp} = 0.22 + 0.0535 \times l(cm)\, pF \tag{8.2}$$

Capacitances and crosstalk are finally given in table 8.2. The numbers are from a full Pspice model.

Experience shows that the capacitance to ground is significatly larger than these values due to edge effects. This will however decrease the crosstalk effect, so the numbers here should be pessimistic.

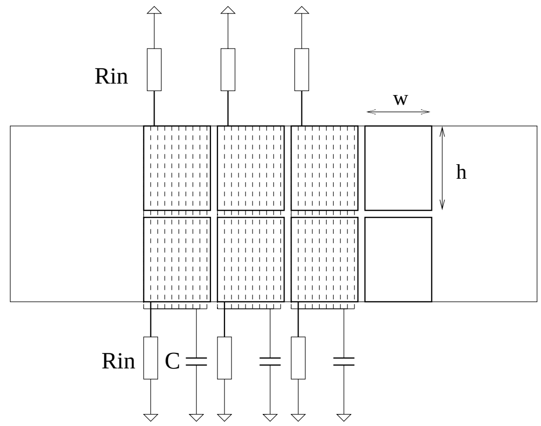

Figure 8.2 *: In R3 we ground the wires at AC and read two cathode pads from the sides. The number of wires that are collected into one capacitor is given by crosstalk requirements.*

8.2 Region 3

In R3 we will read only the cathode signals. The wire pads are grounded at AC (Fig. 8.2). The cathode signals are read from the side. The number of wires that we group into one capacitor is determined by the maximum 'negative' crosstalk that we allow between two cathode pads under the same wire pad. We certainly don't want to connect wires above neighbouring cathode pads (in X) into one capacitor since we would cause unnecessary crosstalk. The question is only if we subdivide the wires above one cathode pad into several wire pads. For now we assume that we create wire pads with the same dimension as the cathode pads. We will see that this is sufficient.

Between the cathodes there are guard strips of 0.5 mm with a gap of 0.4 mm. There is another guard strip on the bottom of the boards. The decoupling capacitor is 1 nF. For a width w cm and height h cm we find a mutual capacitance to the wires of

$$C_{wp} = 0.475hw\, pF \tag{8.3}$$

a detector capacitance of

$$C_{det} = hw(0.475+0.115)+(2h+w)(0.56+0.192+0.403)\, pF = 0.59hw+1.16(2h+w) \tag{8.4}$$

a direct capacitance to ground of

$$C_{pg} = 0.115hw + (2h+w)(0.56+0.403) = 0.115hw + 0.963(2h+w) \tag{8.5}$$

Table 8.3: R3 crosstalk numbers. Capacitances are in pF. Crosstalk in % for 50,100,200 Ω.

Station	C_{pw}	C_{det}	C_{pg}	C_{ppx}	C_{ppy}	50	100	200	neg
M1	4.75	30.3	23.3	1.92	0.192	1.21	2.27	3.87	-1
M2	15	50	30.0	2.4	0.48	1.26	1.97	2.77	-3
M3	21.5	56	33.8	2.6	0.52	1.21	1.79	2.4	-4.3
M4	40	90	43.2	2.8	1.11	1.11	1.6	1.98	-8
M5	46	140	47.	3.	1.2	1.13	1.56	1.97	-9.2

a mutual pad-pad capacitance in X of

$$C_{ppx} = 0.192h\,pF \tag{8.6}$$

and a capacitance to the neighbour in Y that is sitting under the same wires of

$$C_{ppy} = 0.192w\,pF \tag{8.7}$$

The numbers are summarized in table 8.3. The crosstalk fraction numbers are from a full Pspice simulation.

Is is essential to have an input impedance $< 50\,\Omega$ in order to keep the crosstalk between neighbouring pads in X small. In the Y-direction the crosstalk is negative and doesn't cause a crosstalk hit. It will however cause baseline fluctuations at high rates. If we want to reduce this effect we have to group less wires into one capacitor.

In M4 and M5 we OR horizontal pads into one logical channel. Therefore the crosstalk will be even reduced. Experience shows that the capacitance to ground is significantly larger than these values due to edge effects. This will however decrease the crosstalk effect, so the numbers here should be pessimistic.

8.3 M4,M5,R1,R2

In these regions we read a 12x8 chess-board of cathode pads, the wires are grounded at AC (Fig. 8.3). The wire pads have the same size as the cathode pads (in X). The signals are read with traces running on the bottom side of the circuit board. The signals traces should run parallel to the wires since then we can take advantage of the fact that the crosstalk along the wire and the direct capacitive Pad-Pad crosstalk cancel partly.

To reduce the trace length one could read half the pads to the top and half of them to the bottom. We will however study the system where all the pads are read to one side. The couplings are now different for all the pads. We assume the geometry where we have a 0.4 mm guard strip in between the pads on the bottom of the board only in the Y-direction. The signal lines are as described previously. Due to the high rates in these regions and due to the fact that the readout lines and wires couple many pads together, crosstalk is a crucial issue has to be watched carefully.

We find

$$C_{1A1B} = 0.192h \quad C_{1A2A} = 0.342w + 0.37h \quad C_{1A3A} = C_{1A4A} ... = 0.37h$$

$$C_{1A} = hw(0.475 + 0.115) + 2h(0.56 + 0.403 + 0.192) + w(0.67 + 0.342) + 7h0.96$$

$$C_{2A} = hw(0.475+0.115)+2h(0.56+0.403+0.192)+2w(0.67+0.342)+6h0.96+h(0.37+1.1)$$

$$C_{3A} = hw(0.475+0.115)+2h(0.56+0.403+0.192)+2w(0.67+0.342)+5h0.96+2h(0.37+1.1)$$

etc. until

$$C_{6A} = hw(0.475 + 0.115) + 2h(0.56 + 0.403 + 0.192) + w(0.67 + 0.342) + 7h(0.37 + 1.1)$$

The numbers for all the different regions are listed in Table 8.4

We also have to define how many wires we gather into one capacitor i.e. how large we make the wire pad. We should certainly avoid having the negative wire crosstalk also to the neighbour pads in the X-direction, therefore we should make the wire pad either the same size as the cathode pad or a fraction of it. The maximum is defined by crosstalk requirements and the maximum rate we allow on the wire pad. Let's assume for now that we make the wire pads the same size as the cathode pads. Then the rates on the wire pads in M4R1, M5R1, M4R2, M5R2 are 2, 2.3, 0.7, 0.6 MHz which should be acceptable. The crosstalk numbers for the individual geometries are finally given in table 8.4. We find that the crosstalk is very small due to compensation of negative wire crosstalk and positive pad crosstalk. As shown in the previous chapter the negative crosstalk through the wire is given by $-2C_{wp}/C$, so the smaller pads have smaller negative crosstalk and therefore less compensation. The numbers in the table assume a blocking capacitor of 1 nF. By reducing this capacitor C to 500 pF we completely compensate the positive crosstalk also

Table 8.4: Capacitances and crosstalk for M4,M5,R1,R2. The capacitances are given in pF. The crosstalk fraction in %. The labels refer to Fig. 8.3. The crosstalk numbers in brackets refer to all the cathode pads under the same wire pad which are not direct neighbours.

	C_{1A1B}	C12	C13	C14	C15	C16	C17	C18	C_{wp}
M4R1	0.7	2.3	1.3	1.3	1.3	1.3	1.3	1.3	5
M4R2	1.4	4.7	2.7	2.7	2.7	2.7	2.7	2.7	20
M5R1	0.7	2.5	1.4	1.4	1.4	1.4	1.4	1.4	6
M5R2	1.5	5.0	2.8	2.8	2.8	2.8	2.8	2.8	23
	C1	C2	C3	C4	C5	C6	C7	C8	
M4R1	42	46	48	50	52	54	56	54	
M4R2	97	106	110	114	118	121	125	123	
M5R1	45	51	53	55	57	59	61	59	
M5R2	104	114	118	122	126	130	134	131	
	Crosstalk to pads under the same wire pad (Y) %								
R_{in} (Ω)	50	100	200						
M4R1	0.5(0.13)	1(0.3)	1.5(0.5)						
M4R2	< 0.2	< 0.2	< 0.2						
M5R1	0.5(0.1)	1(0.3)	1.6(0.5)						
M5R2	< 0.2	< 0.2	< 0.2						
	Crosstalk to neighbour pads (X) %								
M4R1	0.3	0.5	0.65						
M4R2	0.5	0.63	0.77						
M5R1	0.33	0.45	0.65						
M5R2	0.5	0.66	0.8						

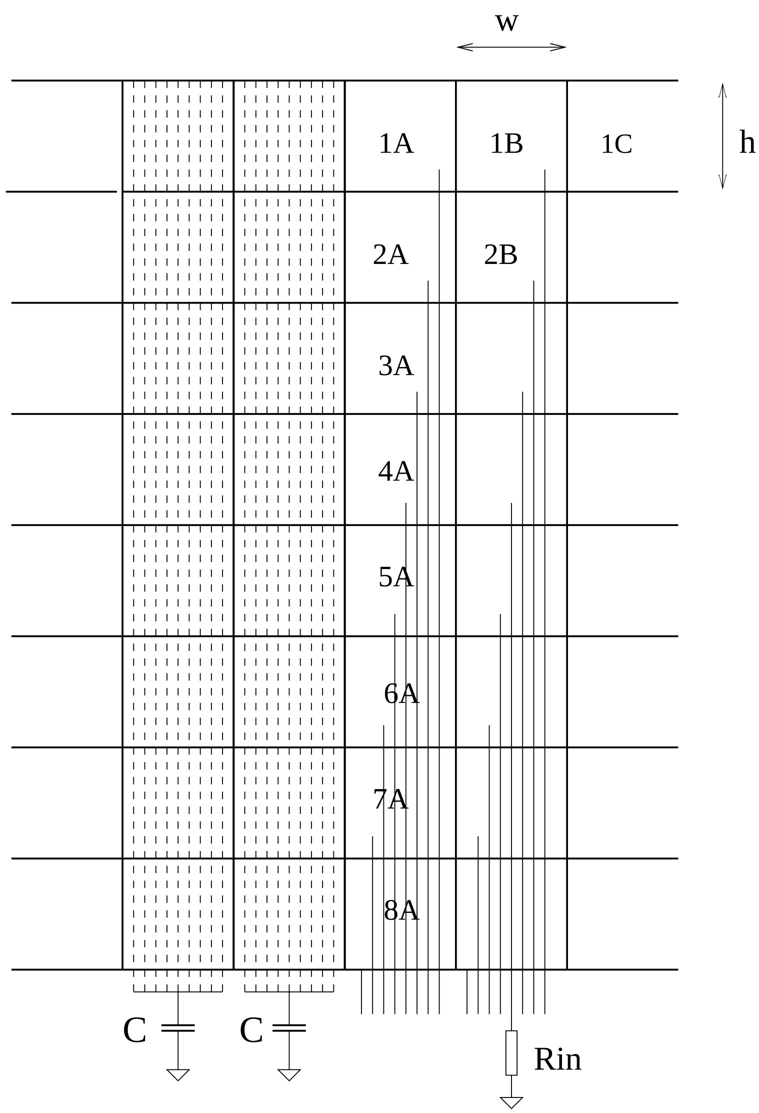

Figure 8.3 *: In R1,R2 of M4,M5 we read an array of cathode pads. The wires are parallel to the readout lines and are grounded at AC. The signal lines are running on the bottom side of the circuit board.*

for the small pads.

To conclude: If the signal lines run parallel to the wires and if the wire pads have the same X-dimension as the cathode pads, a decoupling capacitor of 1 nF reduces the crosstalk that is introduced by the signal lines by a large amount.

8.4 M2,M3,R1,R2

In these stations we read a 8x8 chess-board of cathode pads and in addition we read the signal from the wire pads (Fig. 8.6). The situation is in principle the same as in the previous chapter, however the fact that the wires are not grounded and also the fact that the the wire pads are much smaller than the cathode pads cause some significant differences.

In principle it is an advantage (as before) to read the signal with traces that run parallel to the wires, however due to the fact that we read also the wires we run into space problems in R1. Therefore we will compare both options, i.e. reading all signals along the wire and also reading them horizontally (Fig. 8.5). To see the essential difference we have to look at the crosstalk signals shown in Fig. 8.4. The figures show the crosstalk for M3R2 with $R_{in} = 100\,\Omega$ for the case where we read the signals to the side. The crosstalk along the wire is smaller for the direct neighbours since it compensates with the direct capacitive coupling which has opposite polarity. The coupling through the signal traces is largest for the first neighbour. We have to keep in mind that a large pulse on e.g. pad 5A will fire all the 15 channels 1A-8A and 5A-5H. The wires couple all the pads in the vertical direction, the signal traces in addition couple all the pads in the X direction. If we run the signal traces along parallel to the wires we don't couple the pads in X and we also partly compensate the crosstalk in Y. Therefore it is strongly recommended to run the signal traces parallel to the wires.

The tables 8.5 and 8.6 list capacitances and crosstalk for both readout options. The option reading the signals parallel to the wire is strongly preferred.

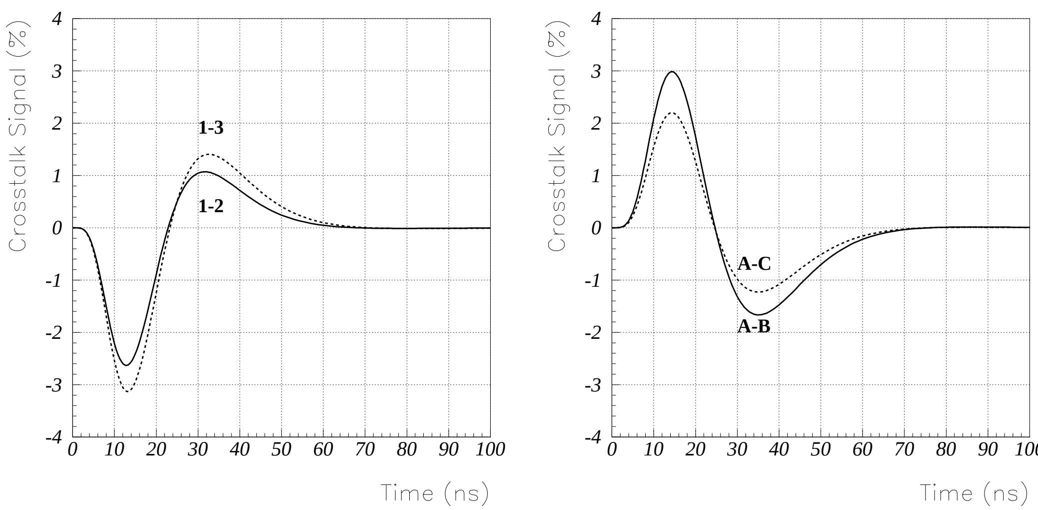

Figure 8.4 : *Crosstalk signals for M3R2, $R_{in} = 100\,\Omega$, pads are read to the side. The left figure shows the crosstalk along the wire. Due to the input resistance of the wire amplifier the crosstalk signal has an overshoot and can cross the threshold. The right figure shows the crosstalk due to capacitive coupling to the signal traces.*

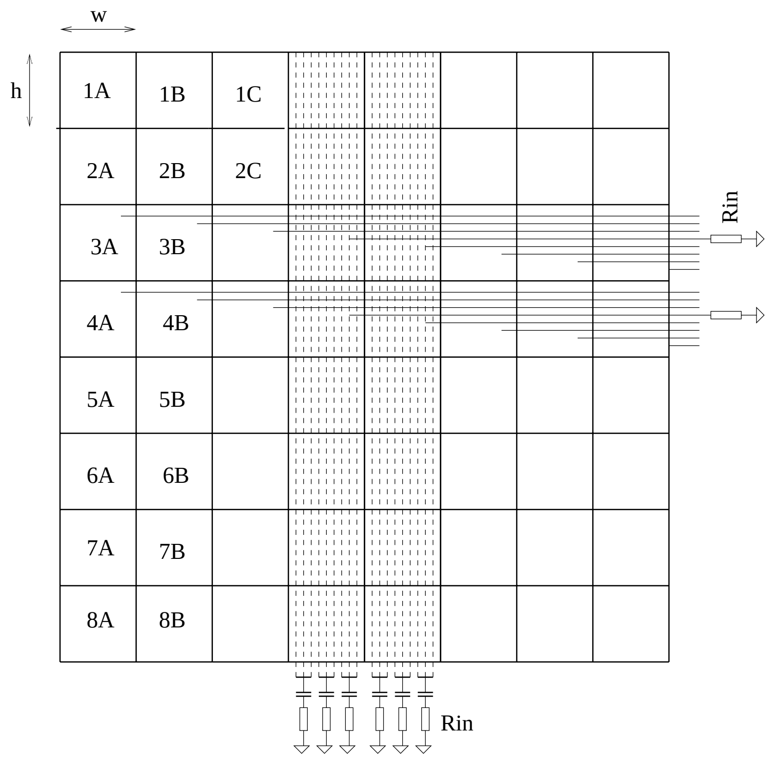

Figure 8.5 *: In R1,R2 of M2,M3 we read the wires in addition to the cathode pads.*

Table 8.5: Capacitances and crosstalk for M2, M3, R1, R2. The signal traces run perpendicular to the wires (Fig.8.5). C1-C8 are the detector capacitances

pF	C1	C2	C3	C4	C5	C6	C7	C8	C_{12}	C_{AB}	C_{AC}	C_{wp}
M2R1	44	49	51	53	55	57	58	57	0.7	2.4	1.4	0.9
M3R1	48	54	56	58	60	62	64	63	0.8	2.7	1.5	1.1
M2R2	85	92	96	100	103	107	111	112	1.4	3.9	2.8	1.9
M3R2	91	99	103	107	111	115	119	120	1.5	4.1	3.0	3.1
%	1-2			1-3			AB			AC		
R_{in}	50	100	200	50	100	200	50	100	200	50	100	200
M2R1	1.2	2.3	3.4	0.8	1.3	2.0	0.2	0.5	1.1	0.5	0.9	1.6
M3R1	1.5	2.5	3.7	0.9	1.4	2.1	0.3	0.7	1.3	0.5	1.1	1.9
M2R2	0.5	1.0	1.6	0.8	1.6	2.3	1.9	2.9	4.0	1.4	2.0	2.9
M3R2	0.5	1.1	1.7	0.9	1.4	2.4	2.0	3.0	4.0	1.5	2.2	3.0

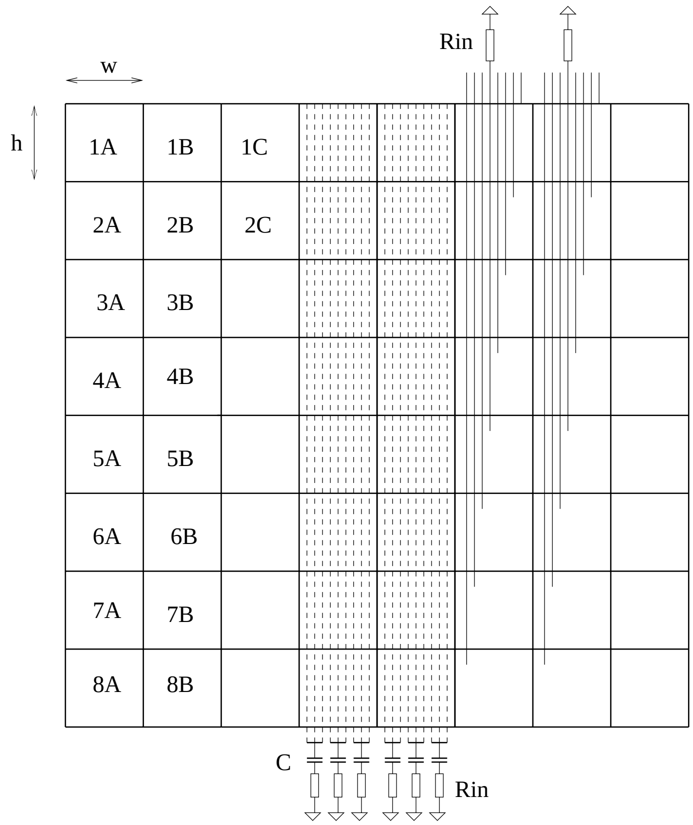

Figure 8.6 *: Reading the signals along traces parallel to the wires cancels most of the crosstalk.*

Table 8.6: Capacitances and crosstalk for M2, M3, R1, R2. The signal traces run parallel to the wires (Fig. 8.6). C1-C8 are the detector capacitances.

pF	C1	C2	C3	C4	C5	C6	C7	C8	C_{AB}	C_{12}	C_{13}	C_{wp}
M2R1	39	44	46	47	49	50	52	50	0.6	2.4	1.1	0.9
M3R1	43	49	50	52	64	56	57	55	0.7	2.6	1.3	1.1
M2R2	50	59	61	62	64	66	67	61	0.6	3.7	1.2	1.9
M3R2	56	64	66	67	69	71	73	66	0.6	4.0	1.2	2.1
%	1-2			1-3			AB					
R_{in}	50	100	200	50	100	200	50	100	200			
M2R1	0.2	0.6	1.3	0.1	0.5	1.2	0.3	0.5	0.6			
M3R1	0.2	0.6	1.2	0.2	0.7	1.3	0.4	0.5	0.7			
M2R2	< 0.1	0.5	1.1	0.5	1.1	1.9	0.3	0.4	0.6			
M3R2	< 0.1	0.4	1.1	0.6	1.3	2.1	0.3	0.4	0.6			

Chapter 9

Baseline Fluctuations

Even if the crosstalk doesn't cause problems by firing neighbouring pads at the same time, the high rate on the wire pads and the fact that the crosstalk signal appears on all the cathode pads under the same wire pad causes baseline fluctuations and dark counts. To study this problem we take a typical crosstalk signal and overlay it randomly according the a given rate and pulse height fluctuation (Landau distribution). Fig. 9.1 shows the crosstalk signals on a cathode pad (under the same wire pad). By applying the given threshold we find the dark count rate, to find the baseline fluctuations we calculate the rms of the trace. Figure 9.2 shows the dark count rate and baseline fluctuation for a crosstalk fraction of 1 % and a threshold of 3 primary electrons. The maximum rate on a wire pad including safety factors is 2 MHz, so we expect a dark count rate of 20 kHz and a baseline rms of 0.3 primary electrons which should be acceptable. For a crosstalk fraction of 2 % however these number start to be problematic, so we should try to keep the crosstalk fraction below 1%.

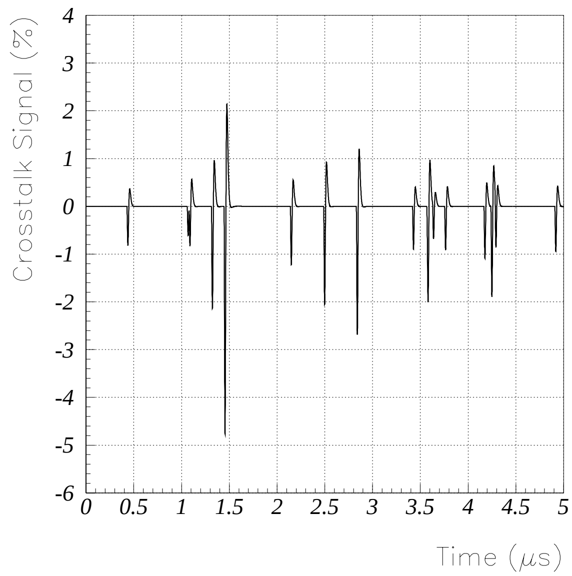

Figure 9.1 *: Crosstalk signals on a cathode pad. The positive overshoot of the signals causes dark counts. The high rate of the crosstalk signals results in baseline fluctuations.*

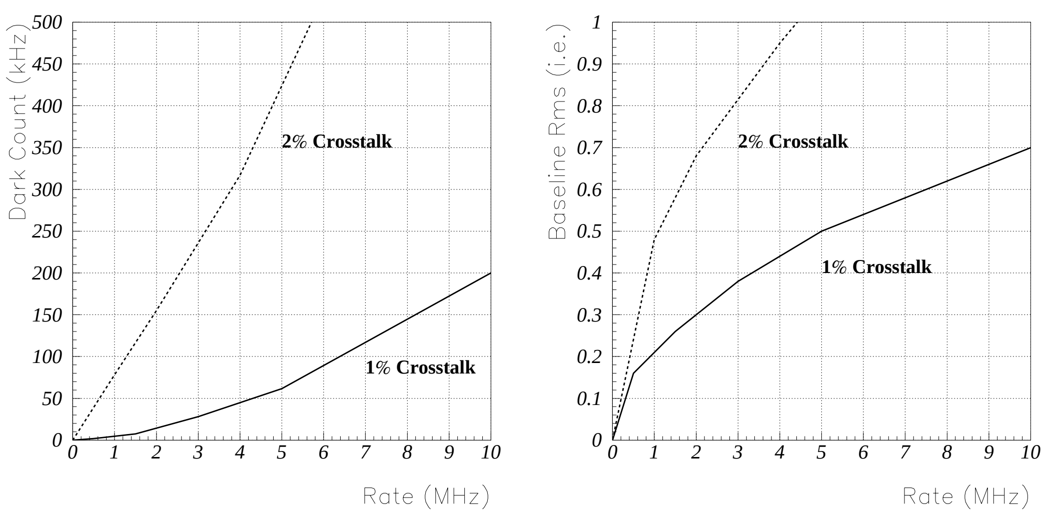

Figure 9.2 *: Dark count rate and baseline fluctuation for M2R2. The threshold is 3e-.*

Chapter 10

Conclusions

- The (unavoidable) directly induced crosstalk results in a cluster size of 1.2 for a threshold of 3e- for a 3 cm cathode pad. Therefore the pad size should be $> 3\,cm$.
- A guard strip of 0.5 mm in between the cathode pads on both sides of a 1.6 mm G10 board together with a pad-guard distance of 0.4 mm limits the pad-pad capacitance to 0.2 pF/cm which is an acceptable number. The resulting gap of 1.3 mm should not cause inefficiency problems, considering the fact that the tracks in the muon system are not always perpendicular to the chamber.
- For the chambers in R1 and R2 we run signal traces (0.25 mm) on the bottom side of the 1.6 mm G10 board, guarded by two grounded traces (0.25 mm) at a distance of 0.25 mm. The guard strips increase the pad-signal trace coupling to an acceptable level, however they increase the pad-ground capacitance significantly.
- An amplifier input resistance of $\leq 50\,\Omega$ reduces the crosstalk to an acceptable level in the entire muon system.
- Since the crosstalk along the wire and the crosstalk due to capacitive coupling have opposite polarity it is advantegous to run the signal traces parallel to the wire in order to partly cancel the crosstalk.

Thanks to Eduard Spiridenkov and Anatoli Kashchuk very useful discussions and suggestions.

Bibliography

[1] A. Vorobyov et. al, Wire Pad Chambers for the LHCb muon system, LHCb internal note (2000-003 muon).

[2] W. Riegler, Detector Physics and Performance Simulations of the MWPCs for the LHCb Muon System, LHCb Internal note (2000-060 muon).

[3] MAXWELL 2D extractor (v4.0), ANSOFT

[4] A. Kachtchouk, W. Riegler, B. Schmidt, Performance of the ASDQ chip, LHCb internal note (2000-062 muon).

[5] B. Schmidt, LHCb muon system by numbers, LHCb internal note (2000 muon).