DEVELOPMENT OF A HIGH MAGNETIC FIELD DRIFT CHAMBER FOR THE CHAOS SPECTROMETER

By

Gertjan J. Hofman

BSc.

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science

in

THE FACULTY OF SCIENCE
DEPARTMENT OF PHYSICS

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
September 1991
© Gertjan J. Hofman, 1991
In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

(Signature)

Department of PHYSICS

The University of British Columbia
Vancouver, Canada

Date 9-Dec-91
Abstract

Design considerations for the Canadian High Acceptance Orbit Spectrometer (CHAOS) led to a set of apparently mutually inconsistent requirements for the inner (WC3) drift chamber. This detector chamber has to be cylindrical, of low mass, have excellent spatial resolution (<200 μm) and operate in a variable magnetic field of up to 1.6 T. This thesis describes the investigations which culminated in the testing of a unique new drift chamber which satisfies all the requirements for the CHAOS WC3.

An overview is given of present drift chamber technology and its application in high magnetic fields. Methods to obtain the space-time relationship are reviewed. In particular, the integral, displacement and trackfitting methods have been applied to prototype chambers. A trackfitting algorithm developed to calibrate a set of wire chambers and correct systematic wire position offsets is presented.

Three types of prototype chambers were designed and constructed. Tests were carried out in beams at TRIUMF to measure the spatial resolution of these chambers in a 1 T magnetic field. The results indicate that a resolution of $\sigma_x \approx 150 \mu m$ can be achieved.

A simplified model of electron transport through gases is used to explain electron drift properties in high magnetic field chambers. A method to resolve the usual left-right ambiguity, proposed within the framework of this model, involves the comparison of the charge induced on diagonally opposed cathode strips mounted parallel to the potential wires. After extensive simulations using the Garfield drift chamber program, a final, unique prototype was designed on which the WC3 chamber to be built for CHAOS is now based. A final beam test in a 1.6 T magnetic field showed that the left-right problem is resolved for track angles between $-45^\circ$ and $+45^\circ$. 

ii
# Table of Contents

Abstract ii  

List of Tables vi  

List of Figures vii  

Acknowledgements xi  

1 Thesis overview and the CHAOS spectrometer 1  
1.1 Introduction ......................................................... 1  
1.2 The CHAOS spectrometer ............................................... 2  
1.2.1 Physics goals ....................................................... 2  
1.2.2 Energy and momentum resolution. ................................. 3  
1.2.3 The Sagane magnet ............................................... 3  
1.2.4 Detector description ............................................... 4  

2 Drift Chambers 9  
2.1 Introduction to chamber principles .................................. 9  
2.2 The electron avalanche ............................................. 12  
2.3 The Garfield program ............................................... 14  

3 Properties of Electron Drift through Gasses 17  
3.1 Introduction ....................................................... 17  
3.2 Drift equations .................................................... 17
### 3.3 Electron Diffusion

21

### 4 The Left-Right Ambiguity

<table>
<thead>
<tr>
<th>4.1 Introduction</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 The application of induced signals</td>
<td>23</td>
</tr>
<tr>
<td>4.3 Solution for the WC3 Chamber</td>
<td>23</td>
</tr>
<tr>
<td>4.4 Position error resulting from the left-right ambiguity</td>
<td>26</td>
</tr>
</tbody>
</table>

### 5 Drift Chambers in Magnetic Fields

<table>
<thead>
<tr>
<th>5.1 Introduction</th>
<th>27</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2 Implication for the CHAOS chamber</td>
<td>30</td>
</tr>
<tr>
<td>5.3 Chamber positioning</td>
<td>32</td>
</tr>
</tbody>
</table>

### 6 Space-time Relationships and Resolution Measurements

<table>
<thead>
<tr>
<th>6.1 Introduction</th>
<th>36</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2 Displacement method</td>
<td>38</td>
</tr>
<tr>
<td>6.3 Trackfitting method</td>
<td>39</td>
</tr>
<tr>
<td>6.4 Chamber Resolution Measurements</td>
<td>43</td>
</tr>
<tr>
<td>6.4.1 Introduction</td>
<td>43</td>
</tr>
<tr>
<td>6.4.2 Measurement of the intrinsic resolution</td>
<td>43</td>
</tr>
<tr>
<td>6.4.3 Track reconstruction resolution</td>
<td>46</td>
</tr>
</tbody>
</table>

### 7 Description of the Chambers

| 7.1 First prototype and Dcal chambers | 49 |
| 7.2 WC3-prototype | 52 |
| 7.2.1 Motivation behind designing a new prototype | 52 |
| 7.2.2 Construction | 54 |
List of Tables

7.1 Cell parameters of the first prototype and calibration chambers. . . . . . . 49
7.2 Cell parameters of the last prototype chamber. . . . . . . . . . . . . . 57
8.3 High voltages applied to the prototype and Dcal chambers. . . . . . . 67
8.4 Measured and expected chamber efficiencies at high incidence rates. .  74
List of Figures

1.1 The z-component of the magnetic field as a function of radius. ............. 4
1.2 The radial component of the magnetic field as a function of radius and
height for a 1 T vertical field. ........................................... 5
1.3 The CHAOS detectors inside the Sagane magnet. .......................... 6
2.4 Adjustable field chamber. ............................................. 11
2.5 A comparison of the Lorentz angle as calculated by Garfield versus mea-
surements [44]. ......................................................... 15
3.6 Electron drift paths from a straight particle track for (a) B_z=0 and (b)
B_z=1 T. Angle β is discussed in section 8.3.4. .......................... 20
4.7 Drift lines for B_z = 1 T at various angles of incidence. ................. 25
5.8 Isochrones separated by 20 ns for a 1 x 1 cm cell, B=1.5 T, calculated by
Garfield. The lines spiraling in towards the anode are drift trajectories.
Two tracks at ±45° are also shown. .................................... 28
5.9 Effect of high voltage variations on drift time, calculated using Garfield
at 1 T. ................................................................. 32
5.10 The Lorentz angles θ, α in the presence of B_z, B_r. Paths d and d' as well
as d'' and d' are coplanar. ........................................... 33
5.11 The x(t) relation from Garfield for different radial components of the
magnetic field. The error shown is x(t)_{B_r=0} - x(t)_{B_r≠0}. ............ 35
6.12 TDC spectrum (counts versus time) of the last prototype (B=1.6 T) and
its integral (drift distance versus time) .................................. 37
6.13 A comparison of the x(t) relation obtained by integration (solid line) and
using the displacement method (triangles) for the first WC3 prototype. 38
6.14 A comparison between the x(t) relations obtained using Garfield and by
fitting cosmic particle tracks, in the absence of a magnetic field .......... 40
6.15 Uncorrected and corrected residuals per TDC bin obtained in the Dcal
chambers for cosmic rays without magnetic field .......................... 42

7.16 Structures of the prototype and Dcal chamber showing the front end and
side view. The aluminium frames are not shown ............................ 50
7.17 Proposed new cell designs, showing which wires/strips are read out ... 54
7.18 Potential contours of the proposed new cell designs ..................... 55
7.19 Contours of the electric field (top) and a vector plot of the electric field
for a rectangular version of the last WC3 prototype. Electric field units
are in V/cm. In these calculation, $V_{\text{anode}} = 2300$ V, $V_{\text{cathode}} = -600$ V,
$V_{\text{strips}} = -300$ V ....................................................... 56
7.20 Top and side view of the WC3 prototype showing the cathode foils,
chamber frame and cell configuration ........................................ 59
7.21 Normalized cathode signals inverted using the SL560 (top) and the Le
Croy 428F fan-in fan-out (bottom) .......................................... 65
7.22 Inverter amplifier circuitry ................................................ 66

8.23 The prototype plateau curve showing the anode and cathode efficiency
versus chamber voltage. No cathode voltage was applied .................. 68
8.24 Typical ADC spectrum showing induced signals on cathode strips ... 69
8.25 Dot plot of the cathode signal amplitude versus drift time ............... 70
8.26 Dot plot of the left-right difference signal versus cathode signal amplitude (bottom) and normalized signal difference $\Delta N_r$ versus signal amplitude (top). ........................................ 71
8.27 Measured $x(t)$ relation at 0° and 48° and the left-right separation $\Delta N_r$ against drift distance for the first prototype. .................. 72
8.28 Schematic diagram of the March and August setup. Distances are not to scale and scintillator $S_3$ is not shown. .................... 75
8.29 Photograph showing the chambers mounted inside the magnet. The prototype chamber is the second from the left. ................. 76
8.30 Schematic of the hardware trigger used in the March and August beam tests. Actual delays and reshaping discriminators are not shown. . . . . 78
8.31 Typical drift time (ns) spectra of the prototype (a) and Dcal chambers (b). ...................................................... 80
8.32 Time distance spectra for four separate collimation windows showing the peaks that were fitted to obtain the time resolution $\sigma_t$ for the first prototype in the 1 T field. ............................... 82
8.33 Resolution measurements of the Dcal (a) and first prototype (b). Graph (a) also shows the raw $\sigma_x$'s, before subtracting the contribution of the other chambers (see equation 6.15). ......................... 83
8.34 Left-right signal ($\Delta N_r$) as a function of drift time from the adjacent (left) and diagonal (right) strips at $B_z=0$ (top) $B_z=0.7$ (middle) and $B_z=1.0$ T (bottom). ............................... 84
8.35 Time to distance relation for the prototype chamber and a dot plot of the ADCs in the Dcal chambers. Shown are the software cuts. ....... 85
8.36 Typical ADC spectrum of a cathode strip in the last prototype for two different cuts (B=1.6 T). ............................... 86
8.37 ADC pulse on a strip against drift (TDC) value for tracks that pass outside the physical boundary of the cell. ........................................ 88
8.38 Left-right separation without magnetic field for adjacent strips (left) and a diagonal combination (right). ........................................ 89
8.39 $\Delta N_{ir}$ against TDC time in ns for all four combination of the strips. Straight tracks in a 1.6 T field. ........................................ 90
8.40 Drift lines from a straight track in high magnetic field in a cell of the WC3 chamber. ................................................................. 91
8.41 $\Delta N_{ir}$ obtained from the combination $D1$ at $+45^\circ$ (left) and $-45^\circ$ (right) in the 1.6 T field. ........................................ 92
8.42 Drift lines from tracks at $45^\circ$ (a) and $-45^\circ$ (b) in the WC3 cell. ....... 92

9.43 Flowchart showing the order of the main tasks performed by the program TRACKFIT. ................................................................. 94
9.44 Monte Carlo results for wire offsets and TDC relations before and after iteration. ................................................................. 97
9.45 Residuals summed per chamber obtained from cosmic ray tracks at $B=0$ T. 99
9.46 Definition of the angle $\theta$ and distances $r$, $x$. ......................... 101
Acknowledgements

The word 'acknowledgement' takes on a completely different meaning in a subject such as nuclear physics. It is impossible to achieve anything by oneself because no one can become a physicist, electronical engineer and machinist in the available time. Even those small pieces of this project that I could call almost mine would not have been successful without the help of the staff at TRIUMF, especially those of the detector facility.

Above all I would like to thank Greg Smith who showed undiminishing enthusiasm for this project and whose ‘outer office’ is always open for discussion and guidance. It is a pleasure to work with an engineer like Pierre who can design anything in half the time and make it work in even less. I would like to thank Jeff for being continuously on shift during the beam tests as well as for correcting this thesis, and Martin for writing software when things got very hectic.

Finally, I want to thank my parents. Regardless of my geographical escapades they continue to support and encourage me in every way they can.
Chapter 1

Thesis overview and the CHAOS spectrometer

1.1 Introduction

The purpose of this thesis is to provide an overview of the development process that led to the final design of the inner drift chamber (WC3) for the CHAOS spectrometer. Various prototypes were built, bench tested and evaluated in tests using pion beams at TRIUMF. Chamber resolution, behaviour in a strong magnetic field, and a solution to the so-called left-right ambiguity were investigated and are evaluated. The first five chapters give a review of chamber technology and physics. Understanding the processes involved will help to justify the choices made in defining the final chamber characteristics. Methods to obtain the time distance relationship are presented in Chapter 6. Chapter 9 briefly discusses a simple trackfitting method and examines the coordinate information obtained from a chamber.

During the development process a total of five new chambers were constructed. The first prototype proved unsuitable for the spectrometer but provided much experience with the chamber electronics and the operation in a real particle beam (December 90). A further three identical chambers, referred to here as the $Dcal$ chambers were built to overcome the lack of available calibration chambers at TRIUMF as well as to investigate the effect of a different cell geometry. The results from a beam test and a test using cosmic rays in March (91) motivated the design of a third (final) prototype on which the planned CHAOS WC3 chamber is now based. A final beam test was
carried out in August (91) with this final prototype.

Suggestions are provided throughout that will help commission the chamber. This thesis should also be useful as reference material for anyone designing magnetic field chambers at TRIUMF or elsewhere.

1.2 The CHAOS spectrometer

1.2.1 Physics goals

The CHAOS detector is being built at TRIUMF to fulfill the need for a spectrometer with a complete $2\pi$ angular acceptance. This will allow a nearly 100% coincidence efficiency for coplanar events and is especially important for the detection of recoil particles from the experimental target. Proposed experiments include $(\pi, 2\pi)$ reactions whose cross sections will provide information on the $N^*\pi\pi N$ coupling constants and provide a test for chiral symmetry QCD models. The measurements will determine the isospin 0 and 2 $\pi\pi$ scattering lengths using reactions such as $\pi^+ p \rightarrow \pi^+\pi^+ n$ and $\pi^- p \rightarrow \pi^-\pi^+ n$ in which both outgoing pions must be detected. Since total cross sections are less than 100 $\mu$b, measurements at single angle pairs of both outgoing pions would require vast amounts of beam time.

Another CHAOS experiment will measure $\pi^\pm p$ polarized scattering asymmetry (analysing powers) at low energies to complete the existing $\pi$-nucleon phase shift database and resolve discrepancies between existing differential cross section measurements. Especially interesting is the ‘$\pi N$ sigma’ term which can be obtained from these measurements and related to the strange quark content of the proton. Recent data give a 10% strange quark content but measurement accuracy is insufficient to give definite answers.
1.2.2 Energy and momentum resolution.

The accuracy of any spectrometer at TRIUMF is limited by the channel resolution unless the detector can measure the energy/momentum of the incoming beam. However, the drift chambers in CHAOS have a drift (dead) time much longer than the 43 ns beam cycle and they can not handle the full beam intensity of up to 40 MHz. The spectrometer therefore aims at achieving a 0.5% $\Delta P/P$ (detector) momentum resolution. This gives an energy resolution sufficient to resolve nuclear levels of the order of a few MeV and is close to the upper limit of the beam channel resolution.

1.2.3 The Sagane magnet

The Sagane magnet chosen for the CHAOS spectrometer is a cylindrical dipole with the $2\pi$ angular acceptance required. The pole diameter (95 cm) and a maximum field of 1.6 T gives the $\int B \cdot dl$ needed for high (400 MeV/c) momentum particles. Furthermore, the open central bore allows easy access to the target. The pole gap is only 20 cm which severely restricts the space available for the chambers and requires the design of very compact high density electronic boards. Modifications to the magnet have included new pole tips to improve the field homogeneity and larger return yokes to allow higher fields. A field map [3] is shown on figure 1.1. The coordinate system used has the $z$-axis along the major component of the magnetic field and perpendicular to the plane of the incoming beam. All chamber wires are parallel to this axis. Figure 1.2 shows the radial component as a function of the radius and height. The varying radial field component influences the positioning of the drift chamber, discussed in detail in section 5.3. It should be noted that Sagane will be operated with weak and strong magnetic fields of both polarities. This places further constraints on the design solutions of the WC3 chamber.
Figure 1.1: The z-component of the magnetic field as a function of radius.

1.2.4 Detector description

Figure 1.3 [6] shows an overview of the target, the inner detectors (PC1, PC2, WC3), the vector chamber (WC4) and the surrounding scintillating and Cerenkov calorimeters inside the magnet. At the centre of the magnet is the target, surrounded by two proportional chambers (PC1 and PC2) which handle incoming and outgoing beam reconstruction and determine the reaction vertex. Due to their small wire spacing and gap (1-2 mm) and consequent short dead time (< 40 ns) these proportional chambers are fast and it is expected that they can handle beam intensities of up to 10 MHz. The 0.5% momentum resolution also forces the use of low density materials. The chambers are constructed using Rohacell and very thin (25 μm) Kapton sheets. Extensive Monte
Figure 1.2: The radial component of the magnetic field as a function of radius and height for a 1 T vertical field.

Carlo simulations have been performed to evaluate the effect of material thicknesses on multiple scattering and momentum resolution. The PC1 chamber has a wire spacing (pitch) of only 1 mm and thus a spatial resolution $\sigma$ of 300 $\mu$m$^1$. The second chamber has a larger, 2 mm pitch, the limitation being readout costs. The angular resolution in the x-y plane of both chambers is $1/4^\circ$. The wire signals are amplified, discriminated and fed into the PCOS readout electronics. There are no cathode wires in PC1 and PC2.

The out of plane acceptance of the spectrometer is approximately ±7° and some

$^1$Quite generally, these resolution parameters are calculated as $\sigma^2 = \int_{-l/2}^{l/2} (\bar{x} - x)^2 dx \approx 300^2 \mu m^2$ where $l$ is the pitch (1 mm in this case) and $x$ the distance from the wire.
z-coordinate information is needed to make the vertical momentum correction, and as an additional aid in determining whether the track originated from the target. For this purpose both PC1 and PC2 have inclined cathode strips, made of copper coated Kapton foils with conductive strips of nickel. In conjunction with the anode information, the induced pulses on these strips describe the z-coordinate of the track. They are amplified through pre-amps, inverted and digitized using the Le Croy FASTBUS analogue to digital converters (ADCs).
Chapter 1. Thesis overview and the CHAOS spectrometer

The original spectrometer design intended to implement three proportional chambers. The three hit wire coordinates unambiguously define a circular arc, allowing a hardware (2\textsuperscript{nd} level) trigger to select particles of the right momentum and polarity. GEANT Monte Carlo showed that the extra mass of this third proportional chamber gives a noticeable increase in the multiple scattering. Secondly, space requirements would force the inner drift chamber to be located outside the pole tips, in an inhomogeneous fringe field that introduces complications that are discussed in section 5.3. It was therefore decided to incorporate the WC3 drift chamber in the 2\textsuperscript{nd} level trigger by splitting the anode signal, thus eliminating the third chamber. Part of the discriminated signal is fed into the logic units while the remainder stops the time-to-digital converters (TDCs) for drift time information. The trigger has been simulated in software [4].

The outer chamber (DC4) is a vector chamber of the type built by the RMC [2] collaboration. It consists of 10 wires per cell, eight being read out for drift time information and two optionally used for charge division readout [7,34] to provide additional z-coordinate information. Field calculations were performed using the Garfield program [5] to investigate the uniformity and the effect of the fringe magnetic field as well as to determine the cathode high voltage distribution.

Lastly, the spectrometer will need accurate particle identification. For this purpose the outer layer consists of a combination of \(dE/dx\) and Cerenkov counters. Mass identification of \(p, d, \pi\) particles from 50 \(\rightarrow\) 280 MeV is achieved using two layers of NE110 scintillators. Pion-electron separation is more difficult because \(e^-, e^+\) particles from \(\pi^0\) decay \((\pi^0 \rightarrow 2 \gamma \rightarrow e^+e^-)\) can emulate pions over a large momentum range. The Cerenkov counter is based on the light intensity difference between high momentum electrons creating a shower of secondary radiating electrons via photon (Bremsstrahlung) conversion, and pions producing little further radiation. The information from these detectors forms the first level trigger, selecting particles of the right
type and events with the right multiplicity. The trigger will operate at 25 MHz and is implemented in ECL logic. A fast first level trigger is essential to gate the ADCs as quickly as possible – any delays require long delay cables on all the analogue signals from the spectrometer.
Chapter 2

Drift Chambers

2.1 Introduction to chamber principles

Drift chambers were developed as an extension of the work carried out on proportional chambers and other gas ionization detectors. The latter were in operation as early as 1908 [8]. The early versions of gaseous detectors were chambers with charged conducting plates. Proportional counters containing many anode wires were not built until 1967 when it was realized by Charpak and co-workers that the expected capacitive effects (cross talk) of multiwires would not interfere with the ability to distinguish individual particles. It is somewhat surprising that drift chambers were not designed until 1968 (Charpak and co-workers) because extensive research on electron and ion transport through gasses had been carried out in the 1920’s (Townsend [9]) in the study of weakly ionized plasmas. Corresponding electron drift velocities had also been measured.

The philosophy behind the drift chamber is that the coordinates of a charged particle can be measured to a precision much greater than the spacing between the anode wires without significantly altering the trajectory. Ionization electrons (and ions) created in a gas when the particle traverses the chamber drift towards (or away) from a positively charged anode wire. If the electric field created near the anode is strong enough, the electrons multiply (avalanche) via collisions and an electric pulse is observed on the wire (see section 2.2). Details on the ionization process and radiation losses due to
charged particles can be found elsewhere [10]. To summarize, in the most commonly used chamber gasses one can expect a primary ionisation of approximately 30 ion-electron pairs per cm of track length. Because the ionization process is a collection of independent events, it follows Poisson-like statistics. If one assumes no losses during drift (such as recombinations), the inefficiency \((1 - \epsilon)\) of the detector is simply the probability that no ionization occurs. Thus \(1 - \epsilon = P_0^n = e^{-n}\), where \(P\) is the Poisson probability function and \(n\) the total number of ionizations. Good efficiency is therefore achieved for detectors only 1 mm thick. The released electrons may have absorbed enough energy to ionize further electron-ion pairs thus creating lumps of charge, or clusters. Very high energy (keV) knock-out electrons are referred to as \(\delta\) electrons and can travel a long distance from a track before establishing thermal equilibrium through inelastic collisions.

Early work also indicated that for a certain range of electron multiplication near the anode wire the measured pulse height is a function of the energy loss of the particle in the chamber region. The Bethe-Bloch equation shows that this loss is a function of particle \(\beta\) at lower energies and of particle mass at higher energies. Chambers using these properties, proportional chambers, have found extensive use in nuclear physics. Note that although PC1 and PC2 are referred to as proportional chambers, they are in fact only position detectors since the anode signal height is not analyzed.

The desire to increase particle tracking accuracy in large volume detectors led to the design of drift chambers [12]. The basic principle is to measure the time it takes for the ionized electron cluster to reach the anode wire. The timer is triggered by the passage of the particle through a scintillator close to the chamber and stopped by the signal on the anode wire. Knowledge of the drift velocity then determines the position of the particle track. Accuracy is only limited by electron diffusion, ionization statistics and knowledge of the space-time \(x(t)\) relation.
Drift chamber designs are extremely varied. In general, any configuration that provides a sufficiently high drift field will work. Parameters such as readout cost, multiple track resolution, magnetic fields and mechanical stability determine the design. Initially, drift chambers were seen as a low cost alternative to proportional chambers because of the reduced number of wires per detection area to read out electronically. Much effort went into chambers of the type shown in figure 2.4, with a drift path length of up to 50 cm [10] and overall sizes of $4 \times 4 \text{ m}^2$ [15]. As will be discussed in greater detail (Chapter 6), the track reconstruction accuracy finally depends on the knowledge of the time-distance relation. Chamber designs such as the one above aim to provide a constant drift field and thus a linear $x(t)$ relationship. This simplifies calibration and, if the chamber is operated in a region where the gas velocity is saturated, makes the drift time less sensitive to variations in temperature and voltage.
Chapter 2. Drift Chambers

Given a strong electric field, the electrons drift towards the anode. The field here necessarily follows a $1/r$ behaviour and close (100 → 200 μm) [11] to the wire the electron avalanche begins resulting in charge gains (multiplication) of up to $10^5$. The observed pulse on the wire is not due to the electrons but due to the ions created during the avalanche. Since the pulse height $dV \propto q \cdot dr$, where $q$ is the total charge and $dr$ the drift distance, the 200 μm that the electrons drift to the wire surface contribute relatively little to the total pulse and are generally neglected when calculating the charge collected on the anode.

2.2 The electron avalanche

The avalanche process deserves a more detailed discussion because the CHAOS detector makes direct use of its geometrical properties. When the electric field exceeds some threshold value, the kinetic energy the electron gains between successive collisions can be sufficient to cause further ionization. The first Townsend coefficient ($\alpha$) is defined as the inverse of the mean free path an electron has to travel before secondary ionization occurs. Typical values are 700 cm$^{-1}$ at fields of $10^6$ V/cm. Such fields are readily obtained close to the surface of a potential wire. It was initially assumed that due to the small wire radius and diffusion that the avalanche completely surrounds the anode wire in the azimuthal direction. This was supported by the fact that induced pulses are observed on all surrounding cathodes. Fischer et al. [13] first designed experiments to determine the extent of avalanche localization. One method consisted of measuring the charge induced by the slowly drifting ions from the anode to the cathode. A clear asymmetry was observed between the pulse height on a cathode wire on the side of the initial ionization and another on the opposite side. Ion drift velocities are low ($v^{-1} \approx 50 \mu s/mm$ versus 20 ns/mm for electrons) thus long integration times
and low rates are needed for such a measurement. In normal drift chamber operation, the ion pulse on the cathodes is not detected. A second method measured the fast induced pulses on the surrounding cathodes produced by the electron avalanche thus determining a charge centre-of-gravity. Asymmetries were again observed.

With the low noise electronics and high gain amplifiers presently available, extensive use is made of the induced chamber pulses. The CHAOS proportional chambers detect the induced pulses on strips inclined at 30° with respect to the anode wire. Strip number combined with the hit wire number will then give z-coordinate information. The ambiguity that arises from not knowing on which side of the anode wire the track passed, or 'left-right' problem (see Chapter 4) is resolved in the WC3 chamber by reading pulses from strips parallel to the wires. Recently, Roderburg et al. [14] have build an induction chamber in which the particle track is localized using only induced signals, making use of the special field geometry near closely spaced wires. Each track position leads to a slightly different azimuthal position of the avalanche. They report accuracies of better than $\sigma_\phi = 30 \mu m$.

Recent computer modelling of avalanches has produced results in agreement with Fischer's measurements. Groh et al. [11] simulated the path of electrons in argon-ethane mixtures by tracking individual electrons released 1 mm from the anode wire. The vast amount of computing time normally needed was reduced by treating Coulomb effects using plasma physics matrix techniques to avoid calculating the contribution of single electron-ion pairs. They concluded that the avalanche starts at 100 $\mu m$ from a 10 $\mu m$ anode wire and has an azimuthal spread of no more than 50°, depending on wire radius but with little dependence on the gain in the investigated range. Furthermore, they concluded that in certain mixtures not one but several avalanches may be created, resulting from chance ionizations as far as 500 $\mu m$ away from the wire. This results in a spread in arrival time of the order of nanoseconds, placing an additional upper limit
to the intrinsic accuracy of drift chambers.

Two other aspects of avalanche formation are relevant to this discussion. When the rate of incident charged particles is high, the slow moving ions created in the avalanche region significantly reduce the electric field around the wire. This *space charge* effect forces the avalanche further out to larger radii. Groh and co-workers observed such a change in radial behaviour.

Increasing the anode voltage increases the pulse height which might seem to improve the signal to noise ratio. However at some electron kinetic energy, another physical process begins to play a role. Photons from excited argon atoms can induce further ionization of surrounding atoms. In the absence of any polarization, photon emission is isotropic and the effect increases the azimuthal spread of the avalanche. This effect may have been observed in our bench tests while investigating the difference in cathode signals at very high gas gains. Photons released from argon atoms can also liberate photoelectrons from the cathodes which will then indefinitely sustain an avalanche. Most drift chamber gasses therefore contain *quenchers*—polyatomic molecules that absorb the electromagnetic energy but de-excite through rotational and vibrational channels.

### 2.3 The Garfield program

The Garfield program played an essential role in the development of the CHAOS drift chambers. Garfield, written and updated by Rob Veenhof at CERN, is a drift chamber simulation program that performs electric field map calculations, signal simulation, drift time calculations and field optimization. The accuracy of the program is limited only by the somewhat primitive physical model underlying the electron transport calculations. The program can be used with magnetic fields but for reasons that will be described, the
Lorentz angle (defined in Chapter 3) predictions are generally too low. A comparison between Garfield’s predictions and recent data is shown in figure 2.5.

The great advantage of Garfield is its ability to handle periodic structures that often occur in drift chambers. The program was mainly used to obtain field maps and a visual image of the electron drift under magnetic fields to give some intuitive insight into the process through which signals are induced on the cathodes.

The program is divided into several sections. The chamber and cell geometry are defined in the cell section. Only wires and infinite planes are allowed – cathode strips have to be simulated by rows of closely spaced wires. The field section calculates
the electric fields using the thin wire approximation. Garfield will display the surface
charge of a wire in the chamber, thus allowing the calculation of the surface fields. This was verified against data [10] for some simple geometries. The surface fields are
essential to determine the minimum diameter of a cathode wire since electron emission
is expected at fields over 30 kV/cm. In the field optimization section the program will
try to match a user specified form of the electric field but the results often require
unrealistic voltages. It was used to obtain a rough estimate of what the necessary
potentials should be but proved very helpful for field calculation in the cells of the
WC4 vector chamber. The chamber gas is specified in the gas section. Garfield only
knows the drift velocities and diffusion coefficients for a few standard mixtures. Data
on argon-isobutane gas mixtures were added using results from Mea et al. [16]. The
most commonly used program routines are called from the drift section. It calculates
time-distance relations (see Chapter 6), draws drift lines from specified particle tracks
and plots and stores isochrones (contours of equal arrival time). Examples are shown
in figures 5.8 and 4.7.
3.1 Introduction

The widespread application of drift chambers renewed interest in the theory of electron transport through weakly ionized plasmas. Electronic computers have enabled the solution of the Boltzmann transport equation with a reduced number of approximations. Rigorous solutions (to second order in the distribution function) have achieved [20] good agreement with experimental data for unmixed gasses in low magnetic fields. The essential weak point in this approach is that the elastic and inelastic electron scattering cross sections have been measured over a wide energy range only for a few gasses. Standard drift gasses use polyatomic molecules for their quenching properties. These molecules have complex rotational and vibrational excitation spectra that make any approximations unreliable. A simplified treatment, based on the approach by Townsend [9] and Palladino [20], adequate to discuss the operation of a chamber in a magnetic field, is presented in this chapter.

3.2 Drift equations

Rather than use the Boltzmann equation, programs such as Garfield calculate the trajectories using much simpler equations of motion, relying only on data for the drift velocity as a function of the electric field. The underlying approximations being made are
that the mean free path is constant over the electron energy spectrum and that the collision intervals are independent of the scattering angle. Especially relevant for CHAOS is the drift velocity in a magnetic field and the resulting Lorentz angle. Garfield's predictions do not compare well with experimental data as was shown on figure 2.5. Discussing the equations of motion will explain how some simple parameterizations [29] may be able to aid calibration of the CHAOS drift chambers.

Under the influence of a magnetic field in the \( y \) direction and an electric field in the \( z \) direction,

\[
\frac{dx}{dt} = \omega z \\
\frac{dz}{dt} = f - \omega x \\
\]

where \( \omega = \frac{eE}{m} \) and \( f = \frac{eB}{m} \).

Integrating twice gives

\[
\omega x = v_{x0}(1 - \cos(\omega t)) + ft + (v_{x0} - f/\omega)\sin(\omega t) \\
\omega z = v_{z0}\sin(\omega t) + (v_{z0} - f/\omega)(\cos(\omega t) - 1)
\]

where the average starting velocities \((v_{x0}, v_{z0})\), assuming isotropic scattering, will be zero. These equations are valid for a time \( t_c \) between two collisions. The mean collision time \(< t_c >\) over the whole energy spectrum is \( \tau \). To average over \( n \) collisions one must integrate the terms \( \sin(\omega t) \) and \( \cos(\omega t) \) over the Poisson like probability that a collision takes place between time \( t_0 \) and \( t_0 + dt \).

For example [9],

\[
< \sin(\omega t) > = \int_0^\infty \sin(\omega t) \frac{e^{-t/\tau}}{\tau} dt \\
= \frac{n\omega\tau}{1 + \omega^2\tau^2}
\]

Thus the mean distance travelled after \( n \) collisions is

\[
< \omega \bar{x} > = \frac{f}{\omega} \frac{n\omega\tau}{(1 + \omega^2\tau^2)} + nf\tau \\
< \bar{x} > = \frac{nf\omega\tau^3}{1 + \omega^2\tau^2}
\]
and similarly
\[
< \ddot{z} > = \frac{nf \tau^2}{1 + \omega^2 \tau^2}
\]

The drift velocities are therefore
\[
v_x = \frac{< \ddot{x} >}{n \tau} = \frac{f \omega \tau^2}{1 + \omega^2 \tau^2} = \frac{eE}{m} \frac{\omega \tau^2}{(1 + \omega^2 \tau^2)}
\tag{3.1}
\]
\[
v_z = \frac{< \ddot{z} >}{n \tau} = \frac{f \tau}{1 + \omega^2 \tau^2} = \frac{eE}{m} \frac{\tau}{(1 + \omega^2 \tau^2)}
\tag{3.2}
\]

The same simple model gives for \(v_z\) in the absence of a magnetic field
\[
v_z = f \tau = \frac{eE \tau}{m} = \mu E
\tag{3.3}
\]

which defines \(\mu\), the electron mobility. Thus the velocity is reduced by the factor \((1 + \omega^2 \tau^2)\) which, measurement shows, can be as large as 3/2. The Garfield equations are essentially those of equations 3.1, 3.2, extended to three dimensions. The Lorentz angle, defined by \(\tan(\theta_i) = \frac{v_x}{v_y}\) is simply equal to
\[
\theta_i = \arctan(\omega \tau) = \arctan(|v|B/E)
\tag{3.4}
\]

where \(v\) is the drift velocity at \(B = 0\). For a typical electric field of 1 kV/cm, a 0.5 T magnetic field setting, electrons drifting in an argon-ethane mixture \((v = 5.3 \text{ cm/\mu s})\) drift at a \(15^\circ\) angle.

The model's main shortcoming is the above mentioned approximation that \(\tau(\varepsilon)\) and \(l(\varepsilon)\) (the mean free path) are both taken to be constant over the whole energy spectrum. If the equations of motion up to first order in \(\partial l/\partial \varepsilon\) [20] are calculated then the more general results below are obtained.
\[
w_\parallel = v_x = \left(\frac{1}{1 + \omega^2 l^2(v)/v^2}\right) \left[\frac{2eE}{3m} \left< \frac{l(v)}{v} \right> + \frac{1}{3} \frac{eE}{m} \left< \frac{\partial l(v)}{\partial v} \right> \right]
\tag{3.5}
\]
\[
w_\perp = v_x = \left(\frac{1}{1 + \omega^2 l^2(v)/v^2}\right) \left[\frac{1}{3} \frac{eE \omega}{m} \left< \frac{l^2(v)}{v^2} \right> + \frac{2}{3} \frac{eE \omega}{m} \left< \frac{l}{v} \frac{\partial l(v)}{\partial v} \right> \right]
\tag{3.6}
\]
Figure 3.6: Electron drift paths from a straight particle track for (a) $B_z=0$ and (b) $B_z=1$ T. Angle $\beta$ is discussed in section 8.3.4.

This result is in fact identical to that obtained using the Boltzmann transport equation to second order in the distribution function. If $\frac{\partial \mu}{\partial v} = \frac{\nu}{\nu} = \tau$ then equation (3.6) reduces to the Townsend results. Programs such as Garfield derive $\tau$ and $\mu$ from the drift data and can therefore be expected to produce good results in the absence of a magnetic field.

Some typical drift paths for straight tracks are shown on figure 3.6 for electrons with and without magnetic field (1 T) for the 1 cm drift space prototype cell. The basic configuration is an anode wire (A), a cathode wire (C) and cathode walls at 1 cm behind and in front of the wires (forming the axes in the above figure). These pictures were generated assuming that thirty equally spaced clusters were generated along the particle track. The electric field in this cell is almost cylindrically symmetric and is as low as 500 V/cm at the centre of the drift space. Thus the drift angle ($\theta_1$ on figure 3.6 (b)) near the mid plane, the line through the chamber wires, is large forcing the electron
towards the back cathode wall. Near the anode wire the electric field increases, the
Lorentz angle is reduced and the path follows the electric field vectors more closely.
Even for perpendicular tracks one would expect adjacent cells to trigger (in the B=1
T case) since the Lorentz force sweeps the electrons across the cell boundary.

3.3 Electron Diffusion

An important limit to the intrinsic resolution of a drift chamber is given by the diffusion
coefficient. The classical diffusion equation
\[ \frac{\partial n}{\partial t} = D \nabla^2 n \]
can be integrated by parts to give
\[ \frac{\partial < x^2 >}{\partial t} = 2D \]  \hspace{1cm} (3.7)
and similarly
\[ \frac{\partial < x^2 >}{\partial x} = \frac{2D}{w} \]  \hspace{1cm} (3.8)
Thus \( \sigma_x^2 = \frac{2D}{w} \) is a measure of the lateral spread the electron swarm undergoes per unit
drift distance. Equation 3.7 can be integrated over the total drift time or equation 3.8
over the drift space to calculate the uncertainty in the arrival time. For the 1 cm pitch
prototype chamber using an argon-ethane (50:50) mixture, the integrated diffusion
coefficient is approximately 3 ns for a single cluster which corresponds to a position
uncertainty of 160 \( \mu \)m. Although this seems large, discriminators are generally sensitive
to the pulse generated by several avalanching electrons and the mean arrival time
spread is some fraction of the number mentioned above. In addition, measurements
[21] indicate that the longitudinal diffusion (in the direction of the electric field) is field
dependent and substantially smaller than the transverse diffusion coefficient \( D \) quoted
in the result above.
Chapter 4

The Left-Right Ambiguity

4.1 Introduction

The left-right ambiguity arises from the inherent symmetry between the tracks to the left and right of the anode wire. Without additional information there is no way of determining on which side the initial ionization took place. This chapter discusses a number of conventional solutions used in low magnetic fields as well as the novel approach developed for use in the WC3 chamber at high fields.

The simplest way to avoid the ambiguity is to use an additional plane of wires (a second chamber) staggered by half the anode wire spacing. This has the additional advantage that the sum of the drift times $t = t_1 + t_2$ for the hits in the two layers is constant in a uniform electric field, allowing a continuous check on the stability of the chambers. Several other methods to determine left from right have been developed, usually involving more than one anode wire per cell. One of the first drift chambers ever designed used two anode sense wires spaced by 1 mm [18]. Tracks traversing the cell fired only one of the two, except when passing in between the wire pair. Later Breskin et al. [34] showed that two very closely spaced (200 µm) anodes provide unambiguous information. Even for inclined tracks only one wire would fire at any given time, presumably due to space charge effects – the electron avalanche around the first wire reduces the effective field around the second. For this technique no timing information is obtained for tracks passing in between the wires.
4.2 The application of induced signals

In 1977 A.H. Walenta [36] wrote a classic paper on the use of induced signals to resolve the left-right ambiguity. In fact, Walenta first commented on possible application of cathode signals in an article published five years earlier but did not develop the idea further. J. Fischer [13] had shown that the avalanche is indeed localized for moderate gains and therefore the ion cloud which drifts away from the anode is not symmetrical in the azimuthal direction. The mirror charge induced in surrounding conductors thus contains information on the direction of the avalanche. In his drift cell, on which our first prototype is based, Walenta was able to resolve left from right for tracks further than 1 mm from the wire using very long charge integration times on the order of $\mu s$. He concluded that the slow ion drift caused the slowly increasing difference between the induced signals on either side of the wire. By contrast, all of our chambers read a fast, differentiated induced pulse achieving equally good separation between left and right.

Further systematic study by Breskin et al. [35] showed that reading out adjacent field shaping wires on both sides of the anode wire (figure 2.4) through blocking capacitors produced the same results. Coupling together more wires on one side of the anode increased the pulse height, improving the signal to noise ratio. After combining more than four cathode wires, the increased capacitance negated this advantage. The ratio of the left-to-right signal was independent of the distance between the cathode field wire being read and the anode wire.

4.3 Solution for the WC3 Chamber

Resolving the left-right ambiguity using multiple planes for the large, variable angle tracks in the CHAOS spectrometer requires a large number of chambers. This increases
the readout cost and, more relevant to the spectrometer, chamber mass. In the simple trackfitting algorithm described in Chapter 9 it was found that even the four planes available during the cosmic ray test did not fully resolve the ambiguity.

The double anode wire approach has several drawbacks for the CHAOS spectrometer. The chamber wires will be crimped for ease of construction and repair, requiring a minimum wire spacing of 2.5 mm. The double wires would leave a large fraction of the cell unuseable. No reference was found to any group having used this approach in a drift cell without electric field shaping in a strong magnetic field. Garfield simulation indicates that unless the electric field is strong enough, the electron drift path is curved to the extent that the avalanche reaches the wires from the back or front rather than from the side, possibly triggering both wires or the wrong one. Finally, the large electrostatic forces between the wire doublet frequently requires additional support, usually a drop of epoxy glue, to ensure even separation over the height of the chamber.

Our results (Chapter 8) indicate good left-right separation by reading either cathode wires or strips, thus confirming Walenta's work. The pulse difference on the adjacent cathode wires in the plane of the anodes can be empirically described as follows [22]

\[ \Delta P = k \cdot q \cdot \cos(\alpha) \]  \hspace{1cm} (4.9)

where \( \Delta P \) is the signal difference, \( k \) a cell-geometrical constant, \( q \) the total induced charge and \( \alpha \) the angle between the line joining the centre of the avalanche to the anode wire and a line joining the anode and cathode wires. For angled tracks the first electron no longer arrives from the cell midplane but along a geometrically shorter path at some angle to the midplane. Therefore \( \alpha \) is increased and \( \Delta P \) decreased. At high magnetic fields the drift lines shown in figure 4.7 are expected, and thus \( \Delta P \) will be zero or even reverse sign as the avalanche arrives from the other side. Garfield simulation suggests that for a wide range of track angles and magnetic fields (of the
same polarity), the cathode strips indicated on figure 4.7 (shaded areas back right and front left) should pick up a large pulse difference. A novel solution to the left-right ambiguity would therefore be to use the induced pulses of the diagonally opposed strips. Since the azimuthal coordinate of the avalanche is largely determined by the electric and the magnetic fields this method is less sensitive to the angle of incidence. Given the symmetry of the cell, reading these strips should be as efficient as reading adjacent strips for the low magnetic field or field off situations. Digitizing only two channels of analogue signal per cell for a given magnetic field polarity maintains the readout cost at the same level as before. No useful information is expected from the
other diagonal strip pair although these would of course be required when the polarity of the magnetic field is reversed.

4.4 Position error resulting from the left-right ambiguity

Ideally, the contribution of the unresolved left-right assignments to the chamber inaccuracy is much less than all other contributing factors. Since the region of ambiguity $x_{\text{max}}$ that remains after digitizing the induced pulses is of the order of 1 mm or less (see Chapter 8), a large cell size would be advantageous. Relatively fewer events would fall in this region close to the anode wire.

On reconstructing the event two strategies can be taken. The position of the track for some $|x| < x_{\text{max}}$ is approximated by the wire position itself or else one blindly trusts the information from the induced pulse down to $x = 0$ with the accompanying risk of doubling the error. In the first case, over a region $2 \times x_{\text{max}}$, the chamber acts like the proportional chambers PC1 and PC2 for which no drift time information is obtained. The corresponding error contribution is $\sigma_p = \frac{1}{3} x_{\text{max}}^2$, the standard deviation of a uniform distribution. The remainder of the chamber has the normal uncertainty in the position. Thus the contribution of the ‘dead zone’ for a 1 cm cell is no more than $\frac{\sigma_p \times x_{\text{max}}}{\text{cell-size}} \approx 60 \mu\text{m}$. 
Chapter 5

Drift Chambers in Magnetic Fields

5.1 Introduction

Since most particle physics experiments employ a magnetic field to measure the particle momentum, drift chambers are often operated inside a magnet or near a fringe field. It was shown in the Chapter 3 that electrons drifting in crossed E and B fields drift at an angle $\theta_l$ to the electric field vector where $\theta_l$ is given approximately by $\tan(\theta_l) = \omega T$. At low E fields (<500 V/cm) and high B fields (>1 T) the Lorentz angle can exceed 60°. This leads to large drift paths, increasing electron losses to recombination. Drift velocity along the electric field is also reduced by the factor $\frac{1}{1+\omega^2 \tau^2}$ (see equation 3.2). This is not necessarily a disadvantage. Townsend [9] argued that since the drift paths are curved but still of average length $\lambda$, the random walk diffusion perpendicular to the magnetic field should be reduced by the same factor, in principle increasing the intrinsic resolution of the chamber.

The time-distance relation becomes highly non-linear under these conditions and difficult to calculate as seen by the incorrect estimate given by the Garfield program. Moreover, as is demonstrated in figure 5.8, there is an asymmetry between tracks at opposite angles of incidence. In one case, there is a drift along the direction of the Lorentz force, in the other case away from it, resulting in the isochrones shown. Isochrones are lines connecting those points in the chamber where drift electrons have equal arrival time at the anode.
Chapter 5. Drift Chambers in Magnetic Fields

Figure 5.8: Isochrones separated by 20 ns for a $1 \times 1 \text{ cm}$ cell, $B=1.5$ T, calculated by Garfield. The lines spiraling in towards the anode are drift trajectories. Two tracks at $\pm 45^\circ$ are also shown.

For small magnetic fields one solution is simply to increase the electric field. In the RMC [2] vector chamber ($B = 0.27$ T, $E \approx 2$ kV/cm) the measured Lorentz angle is only $7^\circ - 8^\circ$ and no special design features have been incorporated. In 1973 Charpak et al. [25] showed that relatively simple chambers could be constructed in which the electric field is adjusted to compensate for the Lorentz force. The chamber is similar to that shown in figure 2.4 but the potentials are modified to give a slanted electric field at an angle $\alpha = \arctan(Bv/E)$, symmetric around the anode. Though approximately calculable, in practice the high voltage angle is adjusted until the arrival
time is minimized for a given track distance. Reported accuracies are of the order of $\sigma = 150 \mu m$ at 1.5 T. Chiavassa [26] et al. built smaller drift chambers of the same type and used the double wire method to resolve the left-right ambiguity. As discussed in Chapter 4, if two anode sense wires are placed close together (on the order of 500 $\mu m$) then only one will fire depending on which side the particle traversed the pair of sense wires [24]. There is a resulting 'dead zone' in between the two anodes, hence the desire to have the wires as close as possible. However, the results of this method during their 1.5 T field test were not described.

Mechanical simplicity stimulated research into drift chamber designs without complex field shaping. Sadoulet et al. [28] constructed a small chamber of the ‘Walenta’ type: one anode wire, one field wire separated by a 7.5 mm drift path and grounded cathode planes 7.5 mm from the anode. They measured the expected non-linear time-distance relation but no loss of efficiency or accuracy at 1.5 T except for large angled tracks close to the field (cathode) wire. Drift velocity saturation (see section 7.2.3) was not observed. De Boer et al. [29] built similar chambers and confirmed Sadoulet’s results. They also showed that the drift velocity could be parameterized with two free parameters which allowed extrapolation of the measured space-time relations to different magnetic fields. From equation 3.2 one can write

$$v_{\|}(B) = \frac{v_0}{1 + (kB/Ev_0)^2}$$

(5.10)

where $v_0$ is the drift velocity without field, $v_{\|}$ is the velocity along the electric field and $k$ is a parameter depending only on gas constants: $k = \tau/(m\mu)$. A second parameter $\gamma$ is inserted in equation 3.4 to correct the Lorentz angle

$$\theta_l = \arctan(\gamma \omega \tau)$$

The drift velocity $v_0$ was known from previous measurement and the velocity $v_{\|}$ was determined for several field strengths. It was found that the time distance relation
constructed using equation 5.10 agreed with those measured directly. Using trackfitting techniques it was verified that time-distance relations for other magnetic fields and angles of incidence could be predicted using to an accuracy comparable to other reconstruction errors. Such a parameterization may be applied to calibrate the CHAOS chamber. Improved resolution was observed for $B=1\ T$ but this was attributed to the reduced relative contribution of electronic error for longer drift times. No attempt has yet been made to measure the reduced diffusion coefficient.

Ever higher accelerator energies have required stronger magnetic fields for particle momentum determination. Sanders et al. [27] tested the slanted electric field drift chamber up to $4.5\ T$ and concluded that electric fields of $5\ KV/cm$ were necessary to compensate the Lorentz angle. The highest field measurements, up to $10\ T$, have been performed by Becker [32] et al.

5.2 Implication for the CHAOS chamber

The important constraints on the CHAOS drift chamber are: a small pitch for short drift times and an accurate second level trigger, low mass materials to reduce multiple scattering, high spatial resolution for track reconstruction and the ability to operate in varying magnetic fields and incident track angles. Over the course of the study demands changed somewhat depending on developments of other parts of the detector. For example, to reduce the multiple scattering it was suggested that one 'chamber box' supported only at the corners of the magnet would provide the support for WC3 and WC4, effectively eliminating the chamber walls. Many field calculations were performed to design a chamber with a minimum number of wires in order to reduce the torque on the proposed chamber box. In the end it was concluded that the combined tension of over 1000 wires would unacceptably deflect the top and bottom of the chamber box.
unless unacceptably thick support walls were used. The preferred design is now an ‘independent’ free standing chamber with Rohacell walls, thin foils, and Noryl rings for crimp pin support.

The slanted electric field approach does not seem suitable for CHAOS. To shape the electric field, electrostatic considerations show that the ratio of cell width to full gap must be at least 1:2 (unlike the 1:1 geometries used in the calibration chambers). A minimum of three cathode wires must be used on each side of the anode to obtain a somewhat homogeneous slanted field. Given a crimp pin spacing of 2.5 mm the smallest possible cell size is 1 cm, which reduces the resolution of the second level trigger. As CHAOS will be operated at fields ranging between zero and 1.5 T of both polarities, (almost) every cathode wire within one cell would need a separate high voltage cable and a complicated system of bussing between cells to allow a reversal of the electric field angle.

The cell type considered to be most appropriate for CHAOS is a simple Walenta type with the addition of cathode strips for left-right determination and field shaping. The cell configuration is shown in figure 7.20. The main disadvantage of this design is that since the electric field will be inhomogeneous and the magnetic field high, a constant, saturated drift velocity can not be obtained. The time-distance relations will be non-linear and dependent on the high voltage stability and mechanical inaccuracies. Some order-of-magnitude calculations using the Garfield program are shown in figure 5.9. The error contribution is insignificant (less than 100μm) in the 1 cm cell if the stability is better than ±10 V.
Chapter 5. Drift Chambers in Magnetic Fields

5.3 Chamber positioning

The previous discussion shows that it is clearly possible to operate high accuracy drift-chambers in strong magnetic fields. Complications arise when the field is inhomogeneous as is the case in the Sagane fringe field. Figure 1.2 shows the radial component of the magnetic field as a function of height (z) and distance from the pole centre (r). It would be convenient to place the chamber outside the pole tips to reduce the space constraints and thus simplify construction. GEANT Monte Carlo studies shows that such a position is near the optimum for momentum resolution. However, at this radius of 40 cm the radial component of the magnetic field varies between 0 and 1.0 T over the full gap of the magnet poles. The question arises of what variation of the field can

Figure 5.9: Effect of high voltage variations on drift time, calculated using Garfield at 1 T.
be tolerated before the uncorrected systematic changes in the drift velocity introduce error of the order of the chamber resolution. In principle some $z$-coordinate information is available from the two proportional chambers and thus corrections could be made off-line. Calibrating the chamber at different fields and angles of incidence is sufficiently complicated however without having to allow for yet additional parameters.

The drift path is affected in two ways. First, the radial component of the $\vec{B}$ field induces a Lorentz angle along the direction of the wire. Second the magnitude of the magnetic field increases as the radial component is added, decreasing the drift velocity. An upper limit on the allowable radial component can be estimated as follows. The path $d'$ followed by a drift electron in a homogeneous magnetic field is shown in figure 5.10. The only change to the arrival time is in the component $V_y$. Since
Chapter 5. Drift Chambers in Magnetic Fields

\[ V_y = \frac{\mu E_y}{1 + \omega^2 \tau^2} \]

a B field of different magnitude gives a relative change of

\[ \frac{V_y}{V_y'} = \frac{1 + \omega'^2 \tau'^2}{1 + \omega^2 \tau^2} \]

making the approximation that the collision time is not a strong function of the magnetic field. The position reconstruction would then be off by \( \Delta d = t\Delta V \) or

\[ \frac{\Delta d}{d'} = \left( \frac{1 + \omega^2 \tau^2}{1 + \omega'^2 \tau'^2} - 1 \right) \]

If it is desired to keep such systematic errors below 100 \( \mu \)m, then, for a 1 cm cell \( \Delta d/d' \approx 0.01 \). Collision times \( \tau \) have been measured by Breskin et al. [31] for argon-isobutane. Taking a nominal B field of 0.8 T one obtains \( B_r^{max} = 0.2 \) T for \( E_x = 0.5 \) kV/cm and \( B_r^{max} = 0.25 \) T for \( E_x = 1.0 \) kV/cm. This is only half the strength of the Sagane radial field at \( r = 45 \) cm. To verify the above estimates, the \( x(t) \) relations for a 1 cm cell with different magnetic field components were calculated using Garfield. As seen in figure 5.11, errors of 100 \( \mu \)m are made when \( B_r \) exceeds 0.2 T. For angled tracks the error reduces proportionally because the path length is geometrically shorter. In conclusion, it was decided to place the chamber inside the pole tips at \( r = 35 \) cm, where the field is strong but uniform over the active region of the chamber (\( \pm 4.5 \) cm).
Figure 5.11: The $x(t)$ relation from Garfield for different radial components of the magnetic field. The error shown is $x(t)_{B_r=0} - x(t)_{B_r \neq 0}$. 
Chapter 6

Space-time Relationships and Resolution Measurements

6.1 Introduction

Ultimately, the position accuracy of any chamber will depend on the precise knowledge of the time-to-distance relationship needed to reconstruct the particle track through the detector. All other sources of uncertainty such as electronic jitter, diffusion and mechanics should dominate the spatial resolution.

There are several methods available. The simplest and least accurate is to integrate the drift-time spectrum such as the one shown in figure 6.12. One observes that

\[
\frac{dn}{dt} = \frac{dn}{dx} \cdot \frac{dx}{dt} = k v(t)
\]

where \(dn/dt\) is proportional to the number of particles in time bin \(t_i\). Integration gives,

\[
x(t) = \frac{1}{k} \int_0^t \frac{dn}{dt} \, dt
\]

if the assumption can be made that \(dn/dx\) is indeed constant over the drift space of the cell. Given the size of the beam relative to the cell size this approximation is usually justified. The equation also implies a constant efficiency over the whole drift cell. If this is not the case, in principle the varying efficiency can be corrected for. The largest contribution to the uncertainty comes from the determination of the constant \(k\). A drift time (TDC) spectrum and its integral is shown in figure 6.12. The integral is normalized by noting that the full width of the spectrum must equal the full width of the chamber cell. It is clear, however, that both the TDC pedestal and
the endpoint of the spectrum are not well defined. In fact, if the angle of incidence of the particle is not exactly normal to the cell then the width of the spectrum will vary since the geometrical path for electrons from angled tracks is always shorter. In addition, care must be taken to eliminate those hits that also trigger neighbouring cells by allowing only those counts for which the TDC time in the cell under investigation is shorter than that of the neighbouring cell. As Djilkibaev et al. [17] have pointed out, substantial numbers of $\delta$-electrons may trigger bordering cells even if the track did not pass through them, thus contributing to the data in the histogram. The integral method gives a good first guess but no more than that. Figure 6.13 shows the $x(t)$ relation obtained by the integral method, normalized by information obtained from the displacement method (discussed in the next section), compared to the displacement method for the first prototype in the absence of a magnetic field.
6.2 Displacement method

In the displacement method [34] the chamber under investigation is mounted on some mechanical device whose accuracy is better than the resolution of the chamber. The chamber is then scanned with a collimated beam. Plotting the displacement against the TDC value one can deduce the TDC offset from the intercept of the curves obtained in the left and right halves of the drift cell. This method will work at all angles and in all magnetic fields. Beam collimation can be achieved simply by using small scintillating fibers, as was done in the first beam test (November 90), or by using two or more additional chambers. A pencil beam can be selected by requiring a coincidence between two narrow time windows in two chambers. Given the left-right ambiguity,
each time gate will define two possible track positions in the cell, one on each side of the wire. Thus four possible trajectories are selected, some of which are usually eliminated by the beam geometry. No knowledge of the chambers in use is needed except a rough estimate of the drift velocity in order to calculate the approximate width of the defined beam. If performed in hardware, the tight coincidence vastly reduces the amount of data written to tape. During the March beam test, all events were written to tape giving the advantage that software coincidence gates could be applied to several parts of the TDC spectrum, in effect providing several simultaneous measurements of the x(t) relation of the chamber under study.

6.3 Trackfitting method

Regardless of the method used to obtain an initial measurement of the space time relation, iterative trackfitting must be used to optimize the resolution of the chamber. Even an accurate knowledge of the drift velocity and electric field are not enough because mechanical tolerance (crimp pin sizes, wire sagging, wall deformation) will contribute to the position uncertainty. Given a sufficient number of coordinate measurements (n ≥ 3 for straight lines) a track is fitted using some first estimate of the space time relation. The difference (residual(t_i)) between measured drift distance using the x(t) relation and calculated drift distance using trackfitting (see chapter 9) is recorded and averaged for each hit in each TDC bin t_i. A new polynomial fit f(t) is performed to the data points x_i = f(t_i) + residual(t_i) and the process is iterated until the residuals are minimized. An example is given in figure 6.14 which compares the results given by the Garfield program and iterations on relatively few tracks per cell, (less than 300/cell good hits of cosmic particles) without a magnetic field. The large deviation near the edge of the cell is probably due to the small number of hits – a result of a software cut.
Figure 6.14: A comparison between the $x(t)$ relations obtained using Garfield and by fitting cosmic particle tracks, in the absence of a magnetic field.

Further description of the trackfitting algorithm is given in chapter 9.

A more sophisticated approach was suggested by Dellacassa et al. [19] which reduces the number of iterations needed to obtain the correct $x(t)$ relation. Rather than calculating the drift velocity as a function of $x$ or $t$ and integrating it over the drift space, they write

$$x = (t_0 - T) \times W(t_0, T)$$

where $t_0$ is a TDC offset, $T$ is the measured TDC drift time and $W(t_0, T)$ the average velocity over the interval $t_0 \rightarrow T$. Instead of merely iterating, use is made of the shape of the residual curve.

Let $x_f$ be the fitted coordinate. If the average residual has no systematic error then,

$$\overline{\Delta x} = x_f - (t_0 - T) \times W(t_0, T) = 0$$
Introducing systematic deviations in the TDC offset ($\Delta t_0$) and in the average velocity $\Delta W_0$, then

$$
\Delta x = x_f - (t_0 - \Delta t_0 - T) \times (W - \Delta W)
$$

$$
= x_f - (t_0 - T)W + \Delta t_0 W + \Delta W(t_0 - T)
$$

Thus the average residual for many data points is

$$
\overline{\Delta x} = \Delta t_0 W + (t_0 - T)\Delta W
$$

Fitting an $m^{th}$ order polynomial $\sum_{n=0}^{m} b_n T^n$ to $W$ gives

$$
\overline{\Delta x} = \sum_{n=0}^{m} b_n T^n + t_0 \Delta b_n T^n - b_n T^{n+1} \quad (6.11)
$$

$$
= \sum_{n=0}^{m} (\Delta t_0 b_n + t_0 \Delta b_n) T^n - b_n T^{n+1} \quad (6.12)
$$

If a polynomial fit of $(m + 1)^{th}$ order is performed to $\overline{\Delta x}$, comparing the coefficients of $T^n$ to those in equation 6.12 gives $m + 1$ equations that can be solved for $\Delta b_n$, the only remaining unknowns. During the next iteration, one substitutes $b_n \rightarrow b_n + \Delta b_n$ and the trackfitting is repeated. The great advantage is that the number of iterations is greatly reduced, to perhaps one or two. Such a procedure has not yet been implemented in the trackfitting routine discussed in Chapter 9. Figure 6.15 shows the type of residual dot plot which would have to be fitted in the above method. This example is taken from the Deal chambers using the simpler method described in Chapter 9 before and after iterations. A large asymmetric spread is observed (the projection of which on the residual axis gives the resolution histograms of figure 9.45). A dot plot with zero average residual indicates a fully corrected time distance relationship. Wire misalignments, electronics jitter and diffusion are the remaining causes for the width of the residual.
Figure 6.15: Uncorrected and corrected residuals per TDC bin obtained in the Dcal chambers for cosmic rays without magnetic field.
6.4 Chamber Resolution Measurements

6.4.1 Introduction

Monte Carlo simulations indicate that the position resolution of the WC3 chamber is critical to the overall momentum resolution of CHAOS. It is hoped to achieve a $\sigma_x \leq 150 \, \mu m$ at any magnetic field setting. Various authors have shown that there is no resolution degradation in high fields [10,25], even for chambers without field shaping [28,29,30]. We have measured the resolution of the Dcal chambers and the first prototype at a 1 T field. Two types of measurements should be distinguished. The intrinsic resolution gives the best possible chamber accuracy limited only by physical processes such as diffusion, fluctuation in primary ionization and by electronic and timing errors. The reconstruction resolution is a measure of how well the detector can reproduce the track coordinates. The additional constraining parameters are knowledge of the wire positions and the time-to-distance relation.

This section discusses all of the methods used to determine whether the drift chambers are capable of the resolution needed for CHAOS.

6.4.2 Measurement of the intrinsic resolution

Since there are no devices capable of resolution substantially better than drift chambers, they themselves have to be used in the measurement as their own 'rulers'.

The simplest approach is to create a finely collimated beam of width much less than $2 \times \sigma_x$ and to observe the width of the TDC spectrum $\sigma_t$ of the chamber under study. The spatial resolution $\sigma_x$ is given by

$$\sigma_x = \sigma_t \times v(t)$$

where $v(t)$ is the drift velocity corresponding to TDC bin $t$. The collimation can most
easily be achieved using an identical set of chambers, either in hardware by requiring narrow time coincidences in the trigger, or in software by applying gates in the TDC histograms in two of the chambers. Since one expects $\sigma_{res} < 200 \mu m$, these gates must be no more than 2 or 3 ns wide. In our case, software gates were used and consequently, large amounts of data (over $10^7$ hits) had to be stored on tape.

If three equidistant chambers are available and two are used to define a track, the coordinate at the centre chamber is

$$x_2 = \frac{1}{2} (x_1 + x_3)$$

The resulting peak in the centre chamber due to tracks passing through points $x_1$, $x_3$ has a width that is a weighted sum of the uncertainties in these coordinates. Therefore

$$\sigma_{obs}^2 = \sigma^2(x_2) + \frac{1}{4} \sigma^2(x_1) + \frac{1}{4} \sigma^2(x_3)$$

$$= \frac{3}{2} \sigma^2(x)$$

where the last simplification is justified only if the chambers are identical and $\sigma$ is taken to be constant over the drift space. This method is simple and gives a resolution averaged over the drift space. We however, wanted to measure the resolution as a function of distance from the anode wire to investigate whether it decreases near the edges of the drift cell. In addition the collimation did not occur at the same distance from the anode in the drift cells of the collimating chambers due to beam focussing and curvature.

The resolution calculation for the prototype chamber is performed in two steps. Ideally a gate set in chamber 1 and 3 at position $x_i$ produces a peak at position $x_i$ in chamber 2. This is not the case for the reasons discussed above. Thus, the cell was divided into $n$ sections (typically 5 or 6) within each of which the resolution is assumed constant. A narrow TDC gate was set at or close to the centre of one section in each of
the collimating chambers such that the resulting peak in the middle chamber occurred near the centre of a section. One then obtains equations of the form:

\[
\begin{align*}
\sigma_{obs,i}^2 &= \sigma_{dcal,i}^2 + \frac{1}{4}(\sigma_{dcal,m}^2 + \sigma_{Dcal,i}^2) \\
\sigma_{obs,j}^2 &= \sigma_{dcal,j}^2 + \frac{1}{4}(\sigma_{dcal,k}^2 + \sigma_{Dcal,j}^2)
\end{align*}
\]

(6.15)  
(6.16)

where \{i,j,...m\} refer to the section of the cell. The width of the peak in the middle chamber is the sum of the width due to that chamber plus the width due to the resolution of the other chambers in cell section \(n\). One needs only to set up sufficient equations by going through the rather tedious process of setting software gates and observing where the peak forms in the middle chamber. A mathematical problem-solving program such as MathCad is then used to solve the set of \(n\) equations. The actual coefficients used are different from the ones above because the chambers were not equidistant as in this example.

There are two sources of error in the above procedure. The track curvature in the magnetic field has been ignored. However, the curvature over the chamber spacing (\(\approx 15\) cm) is small and the only error thus introduced is that of the momentum dispersion. Two measured points on the track do not necessarily predict the coordinate in the third chamber unless the momentum of the particles is constant. This effect is analyzed in detail in section 8.3.2. One also needs to have a good knowledge of the drift velocity before being able to calculate \(\sigma_z\), the spatial resolution. Therefore some time-to-distance calibration has to be performed. Results and errors are discussed in chapter 8.
6.4.3 Track reconstruction resolution

Although the intrinsic resolution of the chamber may be sufficient, reconstruction of the event might not be feasible to that level of accuracy. In the CHAOS spectrometer, the chamber positions will (initially) not be very well known as they are independently mounted inside the magnet. Other large particle detectors may have gravitational or electrostatic wire sagging that limit the knowledge of the wire coordinate. Trackfitting is therefore a much better approach since it directly provides the resolution that can be expected in an actual experiment. This section discusses a method to extract the actual resolution of a single chamber from fits in a set of chambers.

Three or more layers must be available and a best track is fit for each set of hits using an algorithm such as the one described in section 6.3 and Chapter 9. All points, including the one of the chamber under study are included. The residuals between the fitted track distance and drift position provided by the chamber are histogrammed for each wire or chamber layer. Fitting a Gaussian to the residuals gives a $\sigma_x$ resolution for each layer directly. This width will be smaller than the actual resolution of the plane because the track fit has been weighted by that plane itself. The following solution is only applicable to straight tracks, a useful case because even in a magnetic field high energy cosmic ray tracks may have insignificant curvature. The actual chamber resolution can be extracted as follows. The chamber planes are parallel to the x-z plane with y-coordinate $y_i$. To avoid the infinite slopes, the track fit will be parameterized in the form

$$x = m \times y + b$$

A possible $z$-component of the track will not be observed in the chambers. The residual is therefore,

$$x_{exp} - x_{fit} = x_{exp} - m \times y_i + b$$

(6.17)
where $x_{fit}$ is the fitted (predicted) x-coordinate at plane $y_i$ and $x_{exp}$ the measured value from the chamber using the $x(t)$ relation. Thus

$$\sigma_{obs}^2 = \sigma_{obs}^2(m \times y_i + b - x_{exp})$$  \hfill (6.18)

In other words, the observed residual is a function of the slope, intercept and $x_{exp}$ from the chamber. The aim is to isolate the $\sigma(x_{exp})$ for one specific chamber. This variance will be denoted by $\sigma_{res,i}^2$ for chamber $i$. The coefficients $m, b$ are calculated using a $\chi^2$ minimization:

$$b = \frac{1}{\Delta} \left( \sum y_i^2 \sum x_i - \sum y_i \sum y_i x_i \right)$$

$$m = \frac{1}{\Delta} (N \sum y_i x_i - \sum y_i \sum x_i)$$

where

$$\Delta = N \sum y_i^2 - (\sum y_i)^2$$

and the $x_i$'s are given by the time-distance relation for each hit cell. One can substitute these forms into equation 6.18. The results are greatly simplified if one requires that $\sum y_i = n \bar{y} = 0$ [49] which is always possible by an appropriate transformation. One finally obtains

$$\sigma_{obs,i} = \frac{\sigma_{res,i}}{n} \sqrt{\sum_{j \neq i} \left( \frac{y_j y_i}{y^2} + 1 \right)^2 + \left( \frac{y_i^2}{y^2} + 1 - n \right)^2}$$ \hfill (6.19)

As previously, this equation holds only if the chambers are identical. To obtain the resolution as a function of distance, one would have to group the tracks per TDC bin as discussed previously. Equation 6.19 has been tested using Monte Carlo data by generating drift distances with a given standard deviation for four equidistant chamber planes and reconstructing the events (see Chapter 9). In this example, with $n = 4$ and
\[ y_1 = -y_4, \quad y_2 = -y_3 \text{ gives} \]

\[ \sigma_{obs,2} = \sigma_{obs,3} = \sqrt{0.7} \sigma_{res-2,3} \]

and

\[ \sigma_{obs,1} = \sigma_{obs,4} = \sqrt{0.3} \sigma_{res-1,4} . \]

The measured width of the residual curve corrected by the above factors reproduced exactly the standard deviation with which the drift times were generated.
Chapter 7

Description of the Chambers

7.1 First prototype and Dcal chambers

The first prototype chamber was designed [33] with the aim of investigating the left-right ambiguity according to specifications in a paper by A.H. Walenta [36]. As spatial resolution measurements in a magnetic field were needed and no appropriate calibration detectors were available at TRIUMF, three more identical drift chambers, the 'Dcal' chambers, were built. All the chambers are flat, planar chambers with an active area of approximately $20 \times 20 \text{ cm}^2$ and the wires soldered on a G10 midplane circuit board. Figure 7.16 shows the general features of these chambers. Dimensioning details are given in table 7.1.

The G10 wire midplane contains all the decoupling circuitry and, for the first prototype, the pre-amplifier circuitry. Two rectangular frames of G10 on either side of this plane set the chamber gap. A further pair of 1/4" G10 frames have the cathode

<table>
<thead>
<tr>
<th>Cell parameter</th>
<th>First prototype</th>
<th>Dcal</th>
</tr>
</thead>
<tbody>
<tr>
<td>anode wire φ (μm)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>cathode wire φ (μm)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>cathode strip width (mm)</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>half-gap (mm)</td>
<td>5 changed to 10</td>
<td>5</td>
</tr>
<tr>
<td>pitch (drift space) (mm)</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 7.16: Structures of the prototype and Dcal chamber showing the front end and side view. The aluminium frames are not shown.

strip foils glued on one side and an aluminized-Mylar foil on the other. Gas tightness is ensured by using rubber O-rings and two aluminium frames to bolt the layers together. Only positive anode voltages were applied. The aluminium foil and outer aluminium frames act as a grounded shielding plane to reduce interference from outside high frequency sources. Care was taken to interconnect all metallic parts of the chamber. Copper braid or tape was used to improve the contact between parts of the circuit board and chamber body. To avoid ground loops the whole chamber was connected to only one external ground, the pre-amplifier power supply. Inside the Sagane magnet, trial and error showed that it is necessary to connect the high voltage supply ground to the chamber as well.

Gas flows in and out through two lines in the corners of the active area. It also passes through the space between the cathode foils and the shielding foil. This avoids a possible pressure difference between the two layers that would cause a bulging of the cathode readout foil with respect to the anode wires.
Chapter 7. Description of the Chambers

The cathode foils were made from a 18 μm copper laminate on 25 μm Mylar. The foil patterns were designed using the AutoCad program, the negative and positive films were then produced off-site [37]. Substantial effort was put into the developing process because the quality of the cathode signal depends on the quality of the foils. The production process begins by stretching a length of clean foil on a vacuum table and transferring it onto a temporary G10 frame using double sided tape. This ensures constant tension during the development process. The basic photo-chemical process steps are: coating the foils with a photoresist, exposure to ultra-violet light, development to harden the resist and finally etching to remove the unwanted copper from the surface. Parameters such as the method of applying the photoresist, the strength of the etchant and exposure times all affect the result. Air-brush spraying was one of several techniques used to apply an even layer of photoresist but best results were obtained by simply brush painting a single thick coating and allowing it to dry for several hours. Exposure times with the ultra-violet varied with the thickness of the resist layer. The positive developing process in which the resist reacts on copper areas is relatively easy because one can actually observe the change of colour on the area that is protected. When making thick windows such as laminated copper on Mylar, concentrated and warmed ferricchloride (FeCl$_3$) should be used but for the very thin layer of deposited nickel on Kapton it is essential to dilute the etchant with water to less than 20% of its original concentration. Etching of the nickel foil is still almost instantaneous. Further details can be found elsewhere [39]. Finally, the foils are glued onto the G10 chamber frames using epoxy and the electrical contacts are soldered to them.

Several modifications were made to the first prototype during the initial stages of this study. The half-gap (see figure 7.16) was increased to 1 cm to obtain a better field distribution. The cathode and anode wire pre-amp boards were redesigned to reduce the pick-up noise. Originally, the cathode planes were made of aluminium deposited
on Mylar but after difficulties with the soldering of contacts onto this thin foil they were replaced with laminated copper on Mylar. All the signals were to be amplified by a modified version of the Brookhaven DF1001 chip (see section 7.3). Subsequently, the new Fujitsu MB43458 boards became available [45] during production of the new cathode planes and were mounted instead.

The drift-space of the three Dcal chambers is only 5 mm. These new chambers incorporate many of the improved features of the first prototype such as a solid aluminium support frame and plug-in pre-amp boards (Fujitsu MB43458 chip) for all the readouts. To resolve the left-right ambiguity, cathode strip readout is available on both sides of the cells. The cathode wires are simply grounded.

7.2 WC3-prototype

7.2.1 Motivation behind designing a new prototype

The result from the second beam test (Chapter 8) in a 1 T magnetic field indicated that the Dcal chambers performed satisfactorily. However, the electric field in the 1 cm pitch first prototype was too low. The Lorentz force drives the electrons to the far side of the wire resulting in very long (> 400 ns) drift times and no left-right separation is observed on the cathode strips. With this information in hand, it was decided to build a new prototype, which would also provide experience in building a curved chamber using crimped wires. Designs were made for both a chamber consisting of wires only (to be used in conjunction with the ‘chamber box’ idea) and one with foil strips. The aim was to obtain an improved electric field by applying a negative voltage on cathode wires or strips yet have a large cathode strip surface to read, preferably without the use of high voltage blocking capacitors. A proposed change from the Le Croy FERA adc acquisition system to the Le Croy FASTBUS system significantly reduced the readout
cost per channel and a slightly smaller pitch became affordable.

The linearity of the time-distance relation was another concern in the new design. Calculation with the Garfield program showed that this goal is difficult to achieve given the small cell dimensions employed. The $1/r$ behaviour of the field around the anode wire dominates a large fraction of the cell. Different magnetic field settings will change the minimum electric field needed to obtain a saturated drift velocity (see section 7.2.3). Furthermore, angled tracks will result in a non-linear time-distance relation unless there is complete azimuthal symmetry in the electric field. A box type cell design with a central anode wire surrounded by four or more cathode wires would give concentric isochrones except in the far corners of the cell, but as figure 5.8 indicates, this is never the case for high magnetic fields. Tests showed that the drift time spectrum of the new chamber for straight tracks without magnetic field is indeed more flat than that of the first prototype, resulting in a more linear $x(t)$ relationship.

Figures 7.17 and 7.18 show some of the proposed cell structures and their associated electric potential contour maps. Initially, a wire-only version was planned with each side of the cell having two or more cathode wires to read out and one wire for field shaping. Only a thin gas-tight foil would enclose the cells. In the cathode-strip version chosen for the design of the final WC3 prototype, (top left portions of figures 7.17 and 7.18) a relatively uniform field exceeding 1 kV/cm is achieved by splitting the cathode strip into a readout section and a high voltage section, separated by 1 mm. Tests were done in air to investigate the maximum potential difference that can be applied across two strips. Sparking did not occur until the potential difference was raised to 1000 V, with this threshold expected to increase in the much drier drift gas mixture.

Figures 7.19 (top) shows an informative map of the electric field contours for the chosen prototype. The bottom picture shows the direction of the field vector which, in the absence of a magnetic field is identical to the direction of the electron drift. All
Figure 7.17: Proposed new cell designs, showing which wires/strips are read out.

the calculations were performed with 2300 V applied to the 50μm anode wire, -600 V to the 20 μm cathode wire and -300 V applied to the cathode strips.

7.2.2 Construction

The last prototype design is substantially different from the previous chambers and more similar to that chosen for the final CHAOS design. Figure 7.20 shows the basic components and the cathode strip foil. In order to test two different wire pitches, one half of the chamber was built with a 7.5 mm anode-cathode spacing, the other half with a 5 mm pitch. The use of crimp pins to string the wires simplifies the structures. Two curved Noryl bars supported by steel rods form the frame of chamber. Noryl is
used because it is difficult to drill crimp pin holes in the abrasive G10 with the required consistency. In the absence of a computerized numerically controlled drilling machine at TRIUMF, the drilling was carried out off-site [38]. The requested positioning tolerance was 50 ,um. Note that the actual crimp pin hole diameter is 100 ,um, thus for 25 ,um anode wires the crimping misalignment can be as large as 38 ,um. Gas lines were made of thin copper tubes soldered through holes in the copper laminated G10 side walls.

The foils were developed as described above for the first prototypes. A serious design flaw resulted from the incorrect assumption that the difference between the inner and outer radii could be neglected. The back wall foil was therefore made too large, the
Figure 7.19: Contours of the electric field (top) and a vector plot of the electric field for a rectangular version of the last WC3 prototype. Electric field units are in V/cm. In these calculation, $V_{\text{anode}} = 2300$ V, $V_{\text{cathode}} = -600$ V, $V_{\text{strips}} = -300$ V.
Table 7.2: Cell parameters of the last prototype chamber.

<table>
<thead>
<tr>
<th></th>
<th>7.5 mm pitch</th>
<th>5.0 mm pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>anode wire φ μm</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>anode wire tension gm</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>cathode wire φ μm</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>cathode wire tension gm</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>L/R strip width mm</td>
<td>4.0</td>
<td>2.5</td>
</tr>
<tr>
<td>HV strip width mm</td>
<td>3.0/2</td>
<td>2/2</td>
</tr>
<tr>
<td>half-gap mm</td>
<td>3.75</td>
<td>3.75</td>
</tr>
</tbody>
</table>

front wall too small. Consequently, the misalignments were rather large and affected the induced pulse heights (see section 8.3.4).

In CHAOS, the inner and outer walls will consist of Rohacell with thin, nickel deposited Kapton foils glued onto them. Rohacell, a foam type of material, creates less multiple scattering than other construction materials such as G10. In the prototype, G10 was used instead because no time was available to study the techniques needed to glue foils onto Rohacell. A simple mandril of the correct curvature (r=35 cm) was rolled to facilitate gluing the foils on the G10 without stressing the glue joint. An even pressure was applied while drying by covering the G10 with a plastic sheet, inserting large O-rings between the G10 and the plastic and removing the air with a rotary pump. Results were satisfactory but only after trying several thicknesses of glue. A thin, very evenly spread layer was most successful.

The back and side walls were glued onto the Noryl frame before stringing to provide additional support against the wire tension. Mechanical dimensions are given in table 7.2 above.

The cathode wire diameter was chosen such that the maximum surface field did not exceed the nominal limit of 30 kV/cm. Two different anode diameters were chosen
to investigate whether the diameter has any effect on the left-right resolution close to the wire. An increased wire diameter requires a higher potential to achieve the same electron avalanche size or gas gain. This produces a larger, more radial electric field in the 7.5 mm section.

The stringing of the wires using crimp pins is a relatively simple process, especially when the wires are still accessible. The procedure is as follows: insert the top pins in the Noryl bar and feed the wire through the pin, through the hole in the bottom bar and then through the bottom crimp pin. The bottom pin is inserted and a weight is suspended on the wire from the bottom to obtain the correct wire tension. A special insertion tool is available to force the crimp pins in the Noryl holes. Finally, the pins are crimped and the wire ends trimmed.

The electronics boards are identical to those designed for the Dcal chambers (section 7.3). A distribution board sits on top of the crimp pins using the female ‘burgun-D’ pins and decouples the high voltage from the anodes. A similar board at the bottom of the chamber distributes the high voltages to six different lines, three for each chamber half. Separating the signal board from the high voltage lines allows a larger distance between circuit lines helping to avoid discharges.

The largest production problem proved to be the soldering of contacts to the nickel coated Kapton. The nickel film is only several hundred angstroms thick and a drop of solder will easily evaporate the layer. A low temperature solder was used to attach a thin copper braid from the nickel circuit lines to a distribution connector glued on the outer walls. Sometimes the nickel circuit line broke at a glue joint and loss of signal from some of the strips during the beam test was attributed to bad or failing contacts.

The glued joints of the front and back walls were not as gas tight as hoped and the chamber was operated with a 20% gas loss (vol.) between the input and output lines. Drops of glue were used to seal the crimp pins at the wire exit and around the crimp
Chapter 7. Description of the Chambers

Figure 7.20: Top and side view of the WC3 prototype showing the cathode foils, chamber frame and cell configuration.
pin holes in the Noryl. It should be possible to use drops of solder instead as excess glue reduced the electrical contact to the 'burgun-D' pins.

### 7.2.3 Choice of drift gas

A wide variety of drift gasses are available, with the choice of mixture depending on the specific detector requirements. A high drift velocity gas such as $CF_4$ will be used in the PC1 and PC2 proportional chambers to minimize the drift time thus increasing the rate at which the cell can handle charged particles. High gas gain (electron multiplication) can be achieved with photon quencher components added, generally organic compounds.

Stability of the drift velocity is an important criterion for drift chambers. Ideally the velocity saturates at some electric field value less than that used in the chamber so that small variations due to mechanical tolerances or high voltage instabilities do not significantly affect the arrival time. Constant drift velocities make track reconstruction much easier. Measurements [42] show that the electric field required to reach saturation increases in a magnetic field.

An argon-ethane 50:50 (vol.) mixture has been used for most of the WC3 tests. The drift velocity of this mixture saturates at 1 kV/cm in the absence of a magnetic field ($v_d \approx 5.3$ cm/µm) and is not very sensitive to variations in the gas proportions. Some rough estimates using Garfield indicate that a 3-5% variation in the ethane content do not significantly affect the arrival time.

There are other gasses with properties that might be considered more advantageous. An argon-isobutane mixture has similar properties to argon-ethane but leads to a higher chamber deterioration rate unless a small, carefully controlled fraction of methylal is added [41]. Small amounts of such third components usually have strong effects on the drift properties [42] because the large number of possible molecular excitations changes
the scattering cross sections. An argon-methane mixture has velocity saturation at much lower electric fields but still shows much more variation of the drift velocity over the electric field range relevant to the WC3 (1-2 kV/cm). It also has a higher longitudinal diffusion coefficient and a larger Lorentz angle at any field.

The Lorentz angle can be considerably reduced by using heavier gas components such as xenon mixtures. For example, $\theta_l = 51^\circ$ for argon:ethane but $\theta_l = 33^\circ$ for xenon:ethane at 1.5 T for the same mixtures (50:50 vol.) and electric fields (1.3 kV/cm) [41]. However, the high cost of xenon necessitates a gas recycling system, rendering this option unattractive. A further reason for using standard mixtures such as argon-ethane is that their properties such as diffusion rate and cluster formation have been extensively studied [43,44]. Argon-ethane is also one of the few drift gas types built into the Garfield program, thus simplifying comparison of the model with the experimental results.
7.3 Chamber Electronics

7.3.1 Introduction

The anode wires and cathode strip signals must be amplified, preferably as close to the chamber as possible to reduce noise pick-up. The narrow pole gap of the Sagane magnet requires high density, compact boards. The circuits must be able to handle pulses of up to 10 MV/s slew rate of both polarities. The quality of the anode signal is not critical except that the noise level must be below the discriminator trigger level. For the cathode signal the noise level is crucial because one can not hope for more than a 5% amplitude difference between the signals from the left and right strips. It was found that the noise must be reduced to less than about 5 mV peak-to-peak (pp) on the output of the pre-amplifiers. A second, inverting boosting stage is used for the cathode signals to compensate for the attenuation in the 40 m delay cables.

Designing circuit boards for the wide band amplifiers needed for the short, fast rising pulses proved to be difficult unless exceptional care was taken with the grounding. Most of the circuits oscillated to some extent and this was only eliminated after additional grounding (especially between the circuit board and the drift chambers) and shielding was provided. At these video frequencies all circuit board lines have a capacitance, allowing cross-talk. In addition, ground loops through power supplies lead to feedback. Frequently it was necessary to place all modules in a single NIM bin to reduce oscillations.

7.3.2 Wire chamber pre-amplifiers

The first prototype chamber preamp boards were designed for the DF1001 single channel charge sensitive amplifier of Brookhaven design. It was intended to be used for all of the cathode, anode and cathode strip readouts. The gain of this surface mounted
device is approx 30 db at 1 MHz. During the first months of testing most of the effort went into reducing oscillations that swamped the signal. Finally, it was decided to design a new double sided board with an extended ground surface and well separated signal and power supply lines. The board, designed using the AutoCad package, was produced on-site using a positive photochemical technique. When processing double sided boards, positioning the positive films requires considerable care or the resulting circuit traces would be misaligned. Higher density boards have to be produced off-site.

To obtain full efficiency of the chamber the discriminators must be set at their lowest level (30 mV for the Le Croy 821 quad discriminator). Initial tests showed that for large anode pulses (> 300 mV pp) the second overshoot could pass this threshold and double trigger the data acquisition system. Pole zero filters were built and added on the output to reduce the width and tail of the pulse.

Space requirements inside the Sagane magnet force the use of more compact multi-channel preamplifiers, especially for the proportional chambers. A relatively new chip, the Fujitsu MB43458 was extensively tested for use with all of the CHAOS chambers. The gain, measured at $4.4 \times 10^{-5}$ V/C is approximately the same as the DF1001 but the four channels per dual-in-line package give a significantly higher channel density. No significant cross-talk (< 2 mV) was observed between the channels for real chamber pulses. Most importantly, the chip handles positive pulse amplitudes of nearly the same magnitude as the negative pulse swings. Unlike the DF1001, only a single power supply voltage of 10 V is needed. These pre-amplifiers were successfully installed on the cathode strips of the first prototype chamber and later used to amplify all the signals on the calibration chambers and final prototype. No pole zero filters were necessary for these circuits. Compact double-sided plug-in boards accommodating up to 16 channels were designed by D. Maas of the UBC Physics Department.
7.3.3 Cathode inverters

The image cathode signal is a short rise time positive pulse. Since the commercially available analogue-to-digital converters integrate negative pulses, a method was needed to invert the signals with minimum distortion. During bench tests with the first prototype it became clear that a clean inversion is essential for good left-right separation. Figure 7.21 top and bottom show the normalized left-right signal (see Chapter 8 for a full definition) against drift (TDC) time. Both were taken under similar conditions – same chamber voltage, gas and $\beta$-source – but with different inverters. The bottom diagram shows data taken using the Le Croy 428F linear fan-in fan-outs. This module greatly increased the noise level and the quoted bandwidth is insufficient. Passive circuits (inductor coils) were also tried but the available transformers produced a large over-shoot. Compensation would require some impedance matching or a carefully set ADC gate width to avoid integrating this tail.

Good results were obtained with the Plessey SL560 [47], a single channel dual-in-line video amplifier with a maximum bandwidth of 350 MHz. The simple circuitry designed around this chip (figure 7.22) will drive a 50 $\Omega$ coaxial line and provide enough gain to compensate for the losses in the 120 ns delay cables that synchronize the pulses with the ADC gate. Driven at $V_{cc}=10$ V, the output swing is limited to 900 mV. Resistor $R_3$ sets the gain, presently at a maximum of $v_{out}/v_{in} \approx 1.5$. Amplification can be further increased by disconnecting pin 5 from the voltage supply $V_{cc}$. This increases the collector resistance and thus the gain in the first of the chip’s three transistor stages. Blocking capacitor $C_3$ ensures that the first stage remains correctly biased while allowing amplification for high frequency signals. The internal output-current resistor is bypassed because the 50 $\Omega$ output loading would overheat the last stage. The external resistor $R_4$ is used instead. A single sided, 12 channel prototype board
Figure 7.21: Normalized cathode signals inverted using the SL560 (top) and the Le Croy 428F fan-in fan-out (bottom).
was designed, produced and tested during the December test run. Again, the high bandwidth implies that care must be taken to provide good grounding and preferably the inverters and pre-amplifiers should be powered from the same voltage supply. More compact, 16 channel boards based on this circuit were designed [40] and will be used on all the CHAOS cathode signals including those from the PC1 and PC2 chambers.
8.1 Bench testing the first prototype

All bench tests were performed using the SUSIQ [46] data acquisition system running on a 286 PC. It histograms and tests the data collected by the CAMAC system. Standard Le Croy 2249A 10 bit ADCs and Le Croy 2228 TDCs were used. The first step in the operation of any new chamber is to investigate its efficiency as a function of anode voltage, thus establishing the plateau curve. The efficiency is defined by the counting rate of the chamber in coincidence with two scintillators divided by the coincidence rate of the scintillators alone. The plateau curve of the prototype is shown in figure 8.23. The slower rise of the cathode efficiency is due to the smaller pulse height not passing the 30 mV threshold of the discriminator. Because the left-right separation generally improved at higher voltages, towards the upper end of the plateau curve, all the chambers were operated at high gain. Table 8.3 summarizes the potentials applied to the wires and strips for all chambers and results presented in this chapter.

Table 8.3: High voltages applied to the prototype and Dcal chambers.

<table>
<thead>
<tr>
<th>Chamber Type</th>
<th>anode (V)</th>
<th>cathode (V)</th>
<th>strips (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype I</td>
<td>2100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dcal chamber</td>
<td>2050</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Prototype II 7.5 mm</td>
<td>2450</td>
<td>-600</td>
<td>-300</td>
</tr>
<tr>
<td>Prototype II 5.0 mm</td>
<td>2050</td>
<td>-300</td>
<td>-300</td>
</tr>
</tbody>
</table>
Figure 8.23: The prototype plateau curve showing the anode and cathode efficiency versus chamber voltage. No cathode voltage was applied.

The new DF1001 and MB43458 electronics boards reduced the noise on the cathode signals sufficiently to begin investigation of the signal properties. A typical ADC spectrum is shown on figure 8.24. The first peak in the ADC spectrum is due to induced signals from hits in neighbouring cells and can be removed by including only those events that have an associated TDC value for the wire in the cell under investigation. The resultant peak has the shape of the usual Landau energy loss distribution.

There is no relation between cathode signal amplitude and distance of the track from the wire (figure 8.25) as is to be expected from the statistical nature of the avalanche. The induced charge difference between left and right increases with signal amplitude, but the normalized difference defined by $\Delta N_r = \frac{Q_l - Q_r}{Q_l + Q_r}$ is independent of the pulse height, as shown in figure 8.26. Further analysis shows that the first peak in the ADC spectrum also contains useful information. In agreement with the results of
8.2 November test

8.2.1 Description of the experimental setup

The aim of the first test with the first prototype was to investigate the drift time relationship and the left-right information as a function of drift distance, high voltage and angle of incidence in the absence of a magnetic field. A real particle beam allows a more realistic testing of the amplifier electronics. The cathode and anode pulse heights are different from those obtained from the ruthenium ($^{106}$Ru) $\beta$ sources used for all bench tests because these sources emit electrons below minimum ionizing energies.

1\textsuperscript{comparing $\Delta N_{ir} = \frac{Q_{i+1}^r - Q_{i-1}^l}{Q_{i+1}^r + Q_{i-1}^l}$, where $i$ is the wire number}
Chamber efficiency as a function of incident beam rate was also measured.

In the absence of collimation chambers, three thin, crossed scintillating fibers were used to define the beam. The overlap cross section was approximately $2 \text{ mm}^2$. The chamber was mounted on a computer controlled $x/y$-table capable of 100 $\mu$m adjustments. The simple hardware trigger consisted of a quadruple coincidence between an in beam scintillator and the three fibers. The ADC gate could be generated by any of three anode wires under study. An argon-isobutane (75:25) gas mixture flowing at 100 cc/min was used.

8.2.2 Results

The time distance relation obtained by moving the chamber in steps of 1 mm perpendicular to the beam is shown in figure 8.27 for the two angles, $0^\circ$ (chamber perpendicular...
Figure 8.26: Dot plot of the left-right difference signal versus cathode signal amplitude (bottom) and normalized signal difference $\Delta N_{lr}$ versus signal amplitude (top).
Chapter 8. Results

Figure 8.27: Measured x(t) relation at 0° and 48° and the left-right separation $\Delta N_{lr}$ against drift distance for the first prototype.

to the beam) and 48°. The first results on the left-right separation were satisfactory but not as clean as those obtained during the bench tests. As expected, the cathode signals were smaller and so the inverter gain was set to the maximum. Figure 8.27 shows the $\Delta N_{lr}$ for the cathode strips obtained by combining the data from some of the different chamber positions. There are relatively few incorrect left-right assignments. There is no correlation between wrong assignment and pulse height, indicating that noise is not the cause. The cathode strips provided better left-right information than the cathode wires at all chamber voltages. For the 48° data the avalanche arrived at an angle with respect to the midplane. Thus it was expected to see large $\Delta N_{lr}$ on the diagonally opposed strips and reduced separation on the side-by-side strips. Although this pulse difference was indeed larger for the diagonal strips, even the adjacent strip pulses showed separation and the difference between the two techniques was not as large as expected.
Chapter 8. Results

The gain of the amplifiers, inverters and ADC’s varies between channels. Therefore a gain and offset correction must be made for each combination of strips. All the data shown in this chapter have been adjusted by fitting a straight line to a dot plot of the ADC values of the right and left strips. If \( m \) is the slope and \( b \) the y-intercept of this fit then the calibration factors for the right strip are

\[
\text{gain} = \frac{1}{m} \quad \text{and} \quad \text{offset} = -\frac{b}{m}
\]

It is only necessary to correct the ADC value of one of the two strips. This also saves a substantial amount of computing time.

Rate efficiency results

During the final part of this test the beam rate was increased to investigate the efficiency of the chamber at high intensities. The ultimate rate limitation of a chamber (or multi-track resolution) is determined by the total drift time but the operating efficiency is reduced at much lower rates by the space charge effect (see section 2.2). As the anode pulse height is reduced due to the smaller avalanche, the discriminators trigger on fewer hits. If the space charge effect is limiting the electron gain, the same incident particle rate (no./sec.) spread over a longer anode wire will reduce the saturation effect. The achievable rates can thus be expressed in particles per second per wire-length for a given drift cell width. Thus results quoted here should be treated as order of magnitude estimates since the maximum rate will also depend on the preamplifier gain and discriminator levels.

Particle detection efficiency of the first prototype are shown in the table 8.4 below. The second column indicates the expected rate for one cell of the WC3 having an active area with a height of 9 cm, illuminated with uniform intensity. These results are under-estimated because the 2 cm wide scintillator trigger in the November test did
Table 8.4: Measured and expected chamber efficiencies at high incidence rates.

<table>
<thead>
<tr>
<th></th>
<th>Prototype I</th>
<th>WC3 chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>rate (kHz) per cm</td>
<td>14</td>
<td>126</td>
</tr>
<tr>
<td>rate (kHz) over 9 cm</td>
<td>23</td>
<td>207</td>
</tr>
<tr>
<td>96%↑</td>
<td>41</td>
<td>369</td>
</tr>
<tr>
<td>90%</td>
<td>70</td>
<td>630</td>
</tr>
<tr>
<td>80%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

not fully cover the width of the cell under study and the actual incidence rates may have been substantially higher than those quoted. The Le Croy 2735DC discriminator cards which will be used in CHAOS have a much lower threshold than was used in this test and so detect smaller pulse heights. The smaller wire pitch of the WC3 chamber (7.5 mm versus 10 mm in the prototype) will also allow a higher total beam intensity.

### 8.3 March and August tests with magnetic field.

#### 8.3.1 Description of the experimental setup

The March and August tests shared a similar setup, shown on figure 8.28. The three calibration chambers constructed for the tests were used to collimate the beam. The prototype chamber under investigation was mounted on a remotely controlled x/y table (positioning accuracy 20 μm) at the centre of the magnet. Removal of the SAGANE pole tips increased the gap to 47 cm allowing all chambers to be positioned between the poles, each separated by about 15 cm. This close positioning is essential to reduce the momentum spread (see section 8.3.2). The maximum field is however limited to 1 T in this configuration. No accurate measurement of the magnetic field strength or homogeneity was performed and therefore the magnetic coil current settings were based on a Hall probe survey [48]. For the purpose of this test accurate field values
were not essential. During the August test of the final prototype the magnet was in its normal configuration with the pole tips and shims bolted on thus permitting magnetic fields of up to 1.6 T with the 20 cm gap. Space requirements then forced the Dcal chambers to be moved outside the pole tip area and into the fringe field. Picture 8.29 shows the chambers and mounting hardware used in the March test and in subsequent cosmic ray runs. The delay on the trigger was reduced by locating most of the hardware in and around the M13 beam line area. Signals from the anodes were discriminated using Le Croy 2735 amplifier/discriminator cards and digitized with the Le Croy 4290

Figure 8.28: Schematic diagram of the March and August setup. Distances are not to scale and scintillator $S_3$ is not shown.
Figure 8.29: Photograph showing the chambers mounted inside the magnet. The prototype chamber is the second from the left.
TDC system operating in a common stop mode. The TDC stop was provided by a coincidence of three scintillators. The cathode signals were inverted and boosted close to the spectrometer and delayed through RG174 coax cables to the FERA 4300B ADC system located nearby. This system allowed automatic pedestal subtraction and data compression. Only valid data words were transferred to the CAMAC system, thus reducing the number of words written to tape.

The triggers used for the March and August beam tests were identical and are shown in figure 8.30. Although the trigger is formed as fast as possible to gate the FERA ADC system, the analogue signals still have to be delayed by 120 ns to arrive synchronously. The gate, generated by a triple coincidence and a busy from the computer output register, is 300-400 ns wide to allow for a 100 ns pulse width plus the maximum drift time of all the chambers. An initial concern was that the long gate time would degrade the difference signal because additional noise on the tail of the signal is also integrated. The approach of the previous test (November) where the ADC gate was provided by the hit anode wire signal cannot be used because it would require ADCs with separate gating for each channel hit. No degradation was observed.

8.3.2 Momentum dispersion in the Sagane magnet

Spatial resolution measurement in a magnetic field was one of the main objectives of the second beam test. To measure the intrinsic chamber resolution, all other contributions such as multiple scattering and beam momentum spread must either be insignificantly small or well defined so that they may be subtracted. The multiple scattering component is small, approximately 50 μm for 15 cm of air between chambers and a comparable amount from the chamber foils. Beam momentum spread can be

\[ \Delta y = \theta_{m,s} \cdot \frac{\Delta x}{\sqrt{3}} \]

where \( \Delta x \) is the distance between the chambers and \( \theta_{m,s} \) the scattering angle.
Figure 8.30: Schematic of the hardware trigger used in the March and August beam tests. Actual delays and reshaping discriminators are not shown.
estimated as follows. The beam for the chamber whose resolution is being measured is defined by two of the three other chambers. Two possible tracks for different momenta are shown in figure 8.28. The distances $h_1$ and $h_2$ at the prototype location are

$$h_{1,2} = \rho_{1,2} - \frac{1}{2} \sqrt{4\rho_{1,2}^2 - l^2}$$  \hspace{1cm} (8.20)

where the chord $l$ is the distance between the chambers and $\rho$ the radius of curvature. This equation is only valid if $h$ is measured at $l/2$, the worst case. The measured spread of the beam at the prototype chamber is thus $\delta x = h_1 - h_2$. We require $\delta x \ll 100 \, \mu\text{m}$ to measure a chamber $\sigma$ on the order of 100 to 200 $\mu\text{m}$. In a uniform magnetic field, momentum $p$ and $\rho$ are related by the formula,

$$p = 0.2998 \, qB\rho$$

where $p$ is the momentum in MeV/c, $B$ the field in T, $q$ the particle charge in units of $e$ and $\rho$ is in mm. Therefore,

$$\frac{\delta p}{p} = \frac{\delta \rho}{\rho}$$

where $p$ is the beam momentum. Choosing a magnetic field of 1 T and a pion beam momentum of 250 MeV/c (near the maximum of the TRIUMF M11 beam line intensity), the maximum allowable beam particle radius difference $\delta \rho$ is 15 mm and momentum spread $\delta p$ is 2%. By closing the jaws on the pion channel one can easily obtain $\delta p/p \approx 1\%$. Thus, using equation 8.20, the intrinsic beam width $\delta x$ is reduced to about 40 $\mu\text{m}$. Momentum spread was therefore not considered in the resolution calculations.
Figure 8.31: Typical drift time (ns) spectra of the prototype (a) and Dcal chambers (b).

8.3.3 March beam test results

Resolution measurements

This chamber test aimed to investigate the behaviour of the first (1 cm) prototype in magnetic fields of 0.7 and 1.0 T. The calibration chambers were only used as collimators. As the histogram in figure 8.31 (a) shows, the drift times in the prototype chamber are very long. Using the information from the beam scan (displacement method) or by integrating and differentiating the above spectrum, the drift velocity towards the anode wire can be calculated (see figure 8.35). It is approximately 2 cm/μs over most of the cell, much lower than the zero magnetic field saturated velocity of 5 cm/μs. This implies that the electrons are being carried through the very low field sections of the drift space.

A commonly used data test in the analysis was defined such that for any given event
Chapter 8. Results

the data value was only histogrammed if the associated TDC value represented a drift
time that was shorter than that of a hit in a neighbouring cell. In fact, such double
hits accounted for almost 50% of the data. The prototype spectrum on figure 8.31 (a)
was tested on such a software gate. The TDC spectrum of the calibration chambers
shown on figure 8.31 (b) (on which no special cuts have been made) is much narrower,
even when the different pitches are allowed for. The two large peaks (1,2) are produced
in the regions of high electric field – near the anode and cathode respectively. The
third peak outside the drift range of the cell is only observed with the magnetic field
on. If the shortest-arrival-time test is applied this peak disappears, which is easily
explained by using figure 3.6. Even for straight tracks passing within the physical
boundaries of one cell, electrons are carried into the neighbouring cell due to the $E \times B$
velocity component. The firing of the wire in the neighbouring cell is information that
can be used to determine the left-right ambiguity but probably not for track position
reconstruction.

The chamber resolutions were calculated as described in chapter 6.4. For the Dcal
chamber, no $x(t)$ calibration was done, thus the TDC spectrum was integrated and
differentiated with respect to time. The end points of the TDC spectrum were deter-
mined by extrapolating the fast rise and fall to the time axes after all the hits had
been eliminated that actually belonged to the neighbouring cells. The resulting veloc-
ity distribution varied less than 10% between cells. It is estimated that the error in
the velocity distribution is of the order of this 10% variation and is the dominating
contribution to the error in the resolution. The strong variation of between 5 cm/$\mu$s
and 3 cm/$\mu$s over the drift space gave a large fluctuation in the observed time resolution
$\sigma_t$ as can be observed in figure 8.32. None of the results have been corrected for the
software time-window width, which is set at 3 ns corresponding to a position width
of 40 to 65 $\mu$m. The results for the prototype chamber were calculated assuming the
Figure 8.32: Time distance spectra for four separate collimation windows showing the peaks that were fitted to obtain the time resolution $\sigma_t$ for the first prototype in the 1 T field.

calibration chambers have an accuracy independent of the drift distance. Note that even though the drift velocity is lower over a larger fraction of the cell than in the Dcal chambers and leads to very curved paths, the resolution of $\approx 140 \, \mu m$ is not worse than that of these chambers. The apparent increase of the accuracy with drift distance may be statistical. It does not contradict a $\sqrt{x}$ behaviour of the diffusion since this contribution is still small for such short distances. Errors due to primary statistics and electronics (the TDC’s alone have a 1 ns or equivalent 50 $\mu$m resolution) dominate the uncertainty.
Chapter 8. Results

Figure 8.33: Resolution measurements of the Dcal (a) and first prototype (b). Graph (a) also shows the raw \( \sigma_x \)'s, before subtracting the contribution of the other chambers (see equation 6.15).

**Left-right ambiguity**

The first prototype yielded no useful left-right information even at the lower field setting of 0.7 T. The long ADC integration time ensured that the measured induced pulses were a consequence of several electron avalanches. Some clusters originating close to the edges of the cell may drift around to the other side of the anode wire while those ionized in high electric field regions could arrive on the same side as that of the particle track. The Dcal chamber cells, of only half the size of those of the prototype chamber, have a higher electric field and thus performed far better. The Dcal chamber data are summarized in figure 8.34. Shown is \( \Delta N_I \) calculated using adjacent strips and one of the two diagonal combinations at \( B_z = 0, 0.7 \) and 1.0 T. The adjacent strips resolved the ambiguity well at 0 T but the separation decreased at 0.7 T and very little information was obtained at the highest \( B \) value. As predicted, the Lorentz force resulted in an avalanche behind and in front of the anode wire giving improved separation at high
Figure 8.34: Left-right signal ($\Delta N_{lr}$) as a function of drift time from the adjacent (left) and diagonal (right) strips at $B_z=0$ (top) $B_z=0.7$ (middle) and $B_z=1.0$ T (bottom).
Figure 8.35: Time to distance relation for the prototype chamber and a dot plot of the ADCs in the Dcal chambers. Shown are the software cuts.

fields on the diagonal strips. Note that in all chamber tests at zero magnetic field, the diagonal combination results were never as clean as the adjacent strips. One possible reason is that if the angle of incidence on the chamber is not zero, then there would no longer be a complete symmetry between the two cases. Signal noise could also have played a role. The pulses from the adjacent strips were amplified through the same MB43458 chip. Any pickup or oscillation on the board or chip may have partially cancelled when the integrated charges were subtracted. For strips across the cell, two signals amplified by different circuit boards were subtracted. No other explanations have been found.

The left-right separation was further investigated using tests on dot plots such as figure 8.35 (b) which shows the typical relation between the ADC spectra for two diagonal strips. Large signal difference is observed in the areas labelled box 1 and box 3. A software cut shows that these pulses are from the third peak in the TDC spectrum
and thus caused by electrons that drift in from a neighbouring cell. The data from box 2 are from electrons evenly distributed throughout the drift cell.

### 8.3.4 August test results

The August set up was similar to that shown in figure 8.28 except that the Dcal chambers were placed outside the pole tips. The momentum spread was therefore much larger and no effort was made to measure the resolution of the final WC3 prototype chamber. In addition, the low beam rate for $\pi^-$ at 250 MeV/c would have required very long runs.

The majority of the tests concentrated on using the 7.5 mm pitch section of the new prototype to determine whether the left-right ambiguity can be resolved in a 1.6 T field for all angles of incidence. An anode voltage scan was performed without magnetic field to determine the operating voltage at which good chamber efficiency was obtained while the cathode pulses were well within the range of the ADC. Due to the larger anode wire diameter (50 $\mu$m versus 20 $\mu$m for the first prototype), the plateau region began at a higher voltage. As a result, this section of the chamber was operated at 2450 V. Strip voltages are shown in table 8.3. The anode voltage in the 5 mm pitch section was set to 2050 V, the same operating voltage as the Dcal chambers which have identical wire diameters and drift space.

Two typical ADC spectra in the 1.6 T field are shown on figure 8.36. The gain is slightly too large since some of the pulses in the long tail are outside the ADC range. The first spectrum shows the raw data while the second is gated on the condition that the arrival time in the cell under study is shorter than that of the neighbouring cells. There is a noticeable difference between this histogram and those obtained using the earlier prototypes outside a magnetic field (figure 8.24). More detailed analysis using software tests on the data showed that the deviation from the Landau distribution is
caused by electrons that are ionized in the neighbouring cell but are swept into the cell under study by the Lorentz force, as shown in figure 3.6. One expects there to be relatively few electrons from such tracks compared to the number normally arriving at the anode wire and thus a small signal height is produced. A histogram of the ADC in cell \( i \) conditioned on a hit in cell \( i \) and a hit in cell \( i - 1 \) or \( i + 1 \) for which the track actually passes through cell \( i - 1 \) or \( i + 1 \) shows the expected peak with the correct number of events to produce the shoulder in figure 8.36. For tracks close to the cell boundary (cathode) of cell \( i + 1 \) or \( i - 1 \) one would expect a large number of the clusters to be swept into the cell \((i)\) under study and thus a higher ADC pulse. Tracks that pass well into the neighbouring cell on the other hand would have the vast majority of the electrons drift towards the closer anode wire. A dot plot (figure 8.37) of pulse height in cell \( i \) versus distance away from the boundary of cell \( i \) indeed shows a decreasing pulse size for tracks closer to the neighbouring anode wires \( i - 1 \) or \( i + 1 \).

This result is an additional confirmation that the integrated pulse induced on the
cathode is the sum of the pulses induced by all avalanching clusters and not just the one arriving first. Although the size of the avalanche per cluster fluctuates, a reduced number of initial electrons decreases the signal height.

Unlike those from the Dcal chambers, the ADC spectra of the strips in a cell of the new WC3 prototype do not show the pulse induced by an avalanche in the neighbouring cell. The rectangular geometry of the WC3 cell results in a smaller solid angle subtended by the strips with respect to the anode wire of an adjacent cell. Thus the induced pulse is reduced and below the pedestal subtraction level of the ADCs.

The left-right ambiguity for straight tracks in the absence of a magnetic field is resolved extremely well as shown in figure 8.38. The separation is better than that observed with either the Dcal or the first prototype. No data were taken with the smaller pitch section so no direct comparison can be made between the different wire
Figure 8.38: Left-right separation without magnetic field for adjacent strips (left) and a diagonal combination (right).

diameters. The improved $\Delta N_{ir}$ relative to the other chambers may be explained by the larger pitch to half-gap ratio. The electron clusters drift at smaller angles to the wire mid plane (angle $\beta$, see figure 3.6 (a)). One might therefore expect a smaller spread in the azimuthal direction for all the avalanches that contribute to the signal.

Figure 8.39 shows $\Delta N_{ir}$ for all combinations of the four cathode strips against the TDC time in the 1.6 T magnetic field. The combination that is expected to give the best separation is labelled $D1$ and is also indicated in figure 8.40. The information displayed on figure 8.39 permits determination of the azimuthal coordinate of the avalanche for any drift distance. The difference signal is optimal for tracks near the centre of the cell indicating that there the avalanche arrives directly behind and in front of the anode. This is confirmed by the cross-over of the signals from the side-by-side strips. However, the normalized difference signal does not vanish at the same distance from the anode wire for the front and back strips. This is attributed to the misalignment of the foils
Figure 8.39: $\Delta N_T$ against TDC time in ns for all four combination of the strips. Straight tracks in a 1.6 T field.

during construction of the chamber. If the front strips are not properly centred on the anode wire than the charges induced on the front-left and front-right strips will be equal only if the electron avalanches arrive slightly off-centre. The back strips, if aligned properly, will still see an unequal pulse.

For track in the high field region of the anode, these strips give the correct left-right assignment. For longer drift paths the electrons curve around the anode and the strips pick up an equal amount of charge. At this point the other diagonal combination ($D2$) (lower right corner on figure 8.39) gives incorrect left-right assignment because the left strip actually sees the avalanche from a track to the right of the anode.

During the second part of the test the chamber was rotated $\pm 45^\circ$. The difficulties encountered in positioning a curved chamber at a precise angle with respect to a curved
Figure 8.40: Drift lines from a straight track in high magnetic field in a cell of the WC3 chamber.

track resulted in a ±5° uncertainty in the track angle of incidence. The normalized signals for the diagonal combination $D1$ are shown on figure 8.41. For the $-45°$ angle the results are better than expected. Figure 8.42 (b) indicates that these tracks will ionize clusters some of which, in the absence of a magnetic field, would drift to the front of the anode. The strong Lorentz force carries all clusters to the right side of the anode, inducing pickup on the correct strip. The adjacent strips provide good separation for tracks close to the anode but again $\Delta N_{tr}$ tends to zero for tracks further away.

The separation for $+45°$ incident tracks is not as clear close to the anode wire as in the previous cases. The reduced $\Delta N_{tr}$ is explained with the aid of figure 8.42 (a). For the tracks close to the wire the clusters generated at the back of the wire may drift down the left side of the cell, contributing to the pulse on the left strips of the $D1$ combination. In this case the adjacent strips produced no information while diagonal
Figure 8.41: $\Delta N_{tr}$ obtained from the combination $D1$ at $+45^\circ$ (left) and $-45^\circ$ (right) in the 1.6 T field.

Combination $D2$ indicated the wrong track side for all tracks.

Drift times are shorter by almost a factor of 2 for tracks at $+45^\circ$. The isochrones for the WC3 are expected to look similar to those of figure 5.8. The strong deformation from a circular pattern is caused because in the $-45^\circ$ case electrons are forced to drift through regions of lower electric field, increasing the lorentz angle and producing long drift paths. Incidence at opposite angles results in Lorentz angles that lead clusters to the strong field close to the wire as shown on figure 8.42.
Figure 8.42: Drift lines from tracks at 45° (a) and -45° (b) in the WC3 cell.
Chapter 9

Trackfitting

9.1 Introduction

A simple trackfitting program was written which allows actual (reconstruction) resolution of a chamber to be measured. In addition, the program was used to investigate the correction of chamber and wire positions using the residuals between reconstructed and predicted track coordinates. The latter will be of major concern to CHAOS. With four mechanically independent chambers it will be very difficult to align them with accuracy comparable to the resolution of the chambers. Some technique will have to be implemented to determine chamber rotations, displacements and, as a second order correction, individual wire offset due to bad crimping. Finally, the program also provides some insight into the accuracy of the left-right assignment. Given enough layers (four in our case), $\chi^2$ minimization should converge on the correct track. The left-right assignments given by the strips can then be compared to those of the fitted track.

9.2 Algorithm

No attempt is made here to describe the program in detail but a flow chart of the main algorithm is given in figure 9.43. The program takes as its input TDC values and wire numbers. Two external files provide the physical coordinates of the wires and some initial estimate of the coefficients of the $x(t)$ relation. The TDC values are converted to a distance using a fourth order polynomial.
Figure 9.43: Flowchart showing the order of the main tasks performed by the program TRACKFIT.
The fitting algorithm does not fit a straight line to a set of points. Rather it seeks to minimize the distance between a track and the isochrone that is described by the particular TDC value for each hit wires [50]. The function that is minimized is

$$\chi^2 = \sum_i (D_i - D_i^{fit})^2$$

where

$$D_i^{fit} = \frac{|(m \times y_i + b) - x_i|}{\sqrt{1 + m^2}}$$  \hspace{1cm} (9.21)$$

Here $D_i$ is the drift distance obtained from the $x(t)$ relations, $m$ the slope and $b$ the intercept of the track in the coordinate system defined by the wire coordinates. Variables $x_i$ and $y_i$ contain the wire position and $D_i^{fit}$ is thus the shortest distance between the wire and the track. The assumption is made that the isochrone is circular. This is probably a good estimate for the square cell design of the Dcal chamber at zero magnetic field but is not true at high field for reasons discussed previously (see section 5.1). More sophisticated approximations can easily be implemented.

The actual chi-squared minimization routine is due to Bevington [51] and was chosen mainly for its speed of convergence. Briefly, it searches for a global minimum in the $\chi^2$ space by finding the derivative with respect to the unknown parameters (slope, intercept in this case) and varies the parameters in the direction of maximum slope. Experience has shown that the algorithm can easily be trapped into local minima, therefore great care must be taken to provide good initial estimates of the fitting parameters. First guesses of the track coordinates are made using the hit wire positions corrected by the left-right assignments. It was found that just providing the wire coordinates frequently does not produce the correct convergence. Alternatively all $2^n$ possible combinations of left and right for all $n$ wires could be fitted and the one with the smallest $\chi^2$ selected. The minimization routine is very general. For the trackfit the program receives only
an index pointing to the wire position (independent variable) and the drift length 
(dependent variable). The same algorithm is also used to fit new polynomials to the 
x(t) relations and to fit Gaussians to the residual histograms by providing it different 
functions to minimize.

Once the correct slope and intercept have been found, the residuals $\Delta x$ are col-
lected. The difference between the drift distances from the time-distance relations and 
calculated drift distances (returned by the fitting routine) is summed for each TDC 
bin to correct the $x(t)$ relation. After one iteration (one complete set of tracks) the 
residual is averaged over the number of hits in that TDC bin and added to the existing 
drift distance value at that bin. The procedure for the positioning offset correction is 
similar. Here a sign is added to the residual depending on whether the track passed to 
the left or right of the wire and a correction is made for the track angle of incidence, 
$\theta$. In other words, the wire position offset is

$$\Delta x = \pm (\text{drift} - \text{calculated-drift}) \times \cos(\theta)$$

A wire with a correct $x(t)$ relation but a positive x-offset (wire misalignment) will 
therefore always give a negative $\Delta x$ regardless of which side the track passed. An 
equivalent relation holds for offsets in the y-direction. In CHAOS a similar method can 
be applied except that corrections will be made in the $r$ and $\phi$ directions.

Convergence is very slow if both corrections are made at once. If one has a good 
estimate of relative wire positions then it can be advantageous to fix those parameters 
and iterate to improve only the TDC relation. A first attempt with real data showed 
that, due in part to the small number of tracks used the wires were moved inconsistently 
in all directions. The second implementation of the program allowed the wires to be 
grouped together, for example, all those belonging to one plane. Crimping or soldering 
errors are likely to be substantially smaller than positioning errors of whole chambers.
Indeed, convergence improved when this technique was used. The residuals for the wires in one group are averaged and all wire positions in the group corrected by the same amount. A similar grouping procedure might also be implemented for the $x(t)$ relations for identical cells. In the Monte Carlo results presented in figure 9.44 tracks passed 4 planar layers separated by 20 cm with wires 4 cm apart. The tracks ($10^4$) were generated randomly at all angles. A Gaussian distributed error of $\sigma = 100 \mu m$ was added to the drift distances to give a more realistic chamber simulation. Cell $A$ was offset in the $x$ and $y$ direction resulting in a residual spread around the origin (see

Figure 9.44: Monte Carlo results for wire offsets and TDC relations before and after iteration.
top and bottom left histograms on figure 9.44). If the offset is small (less than 1.0 mm) the two peaks will not be resolved and a broad Gaussian is observed. Cell B's residuals resulted from a run with an incorrect TDC-to-distance relation, producing a shift to one side. After 10 iterations the residual widths were reduced to their intrinsic minima. Corrected by the coefficients calculated from equation 6.19, the width of the lower two histograms correspond to the 100 μm error with which the tracks were generated.

9.3 Application to real data

During the cosmic ray test without magnetic field following the March run, not enough data were collected to properly test the algorithm. Problems with the 4290 TDC system as well as with the ADCs resulted in a lot of short runs. Only around 2500 good hits passed the strict test that all chambers had single hits only and all strips fired. No chamber position information was available except some approximate sizes of the mounting hardware. As no measurement of the x(t) relation at zero magnetic field had previously been performed, the first estimate used in the trackfitting routines was a straight line determined by the end points of the TDC spectrum. The first fits were visually inspected (the program optionally plots the chamber layout, isochrones, fitted tracks and histograms) to make large chamber alignment corrections and to verify the cabling of all the channels. Results are shown in figure 9.45 which shows the residuals for the three Dcal planes and the prototype plane. Dot plot figure 6.15 (b) which is based on these results shows clearly that there are no more systematic deviations. Approximating to first order that the resolutions of all the chambers are comparable and using equation 6.19 one obtains $\sigma_{Dcal} = 190 \, \mu m$ and $\sigma_{Pcham} = 230 \, \mu m$. This resolution is worse than what can be expected for chambers of this type ($\leq 150 \, \mu m$) but is largely due to the small number of hits (≈ 300/wire) and the fact that no individual wire offsets were
Chapter 9. Trackfitting

Figure 9.45: Residuals summed per chamber obtained from cosmic ray tracks at $B=0$ T.
considered in the correction of the time-to-distance relationship. More importantly, these results indicates that given little information on the chamber position and no $x(t)$ calibration one can obtain a true resolution close to that expected.

Far more data were available for the pion beam magnetic field runs. Since all chambers were inside the homogeneous field region, in principle one could fit circular tracks. It is relatively simple to show that the function to minimize is:

$$\chi^2 = \sum \left\{ \frac{D_i^{fit} - |\sqrt{(x - x_c)^2 + (y - y_c)^2} - r|}{r} \right\}^2$$

Here $x$ and $y$ are the wire coordinates. The right hand side of the equation is just the shortest distance between a circle (the track) and a point (the wire coordinate). The three fitting parameters $(x_c, y_c, r)$ are the two coordinates of the circle centre and the radius of curvature. This algorithm has been implemented and tested using Monte-carlo data in a similar fashion as the straight tracks. However, during the March run the position of the chambers had not been recorded. The second problem seems to be that the fitting routine is very sensitive to the starting values. Since the trajectory points form only a small arc of the circle, the starting parameters given by the values of the hit wire positions can be very far off. An alternative method is to approximate the track by a straight line over the cell region and use the minimization function equation 9.21.

9.4 Obtaining the track coordinates in CHAOS.

Obtaining track information for CHAOS from the WC3 chamber is complicated because the time-distance relationship is a function of the track angle of incidence $\theta$ as well as the magnetic field. This section is merely intended to provide some suggestion as to possible approaches, none of which have been fully investigated. If Garfield could accurately predict $x(t)$ relations in a strong field then a table could be calculated for
each angle of incidence and field setting. The two proportional chambers and the eight wire planes of WC4 could be used to obtain an approximate angle of incidence on WC3 and the track coordinate read from the look-up table. During a second iteration the track slope is recalculated and an improved coordinate obtained from the WC3 chamber. The $x(t)$ relation can be defined such that the returned coordinate is the distance from the anode along the wire plane or the distance to the isochrone closest to the track. For rectangular cells in a weak magnetic field, the coordinates are related simply through $x = r / \sin(\theta)$ because (see figure 9.46) the drift angle $\phi$ is equal to the track angle $\theta$. Garfield returns the coordinate of the track in the plane connecting the wires. The look-up table would therefore return the $(R, \phi)$ position of the track where $R$ is the chamber wire plane radius and $\phi$ calculated from the wire number and the drift distance.

It should be possible to improve Garfield’s prediction by entering experimentally
measured drift velocities and Lorentz angles [44] as a function of the magnetic field. The three parameters, electric field, drift angle and velocity completely determine the drift behaviour of the electron clusters. This option should be further investigated. The look-up table \( x = f(t, \theta, B) \) could be corrected as discussed above, by collecting residuals between predicted drift distances and calculated drift distance.

A better reconstruction method could be implemented if it is possible to parameterize the track, involving for example, the unknown particle momentum. A minimization fit could then be applied over all the chambers. This would give the best momentum resolution because the redundant number of planes in the CHAOS spectrometer would compensate for the chamber inaccuracies. A fitting procedure would proceed as follows. The distorted isochrones in the WC3 cell under the influence of a magnetic field can be approximated to a circle over some range of incident angles. A look-up table would return the radius of that circular isochrone given the drift-time and a rough estimate of the track angle. A fitting routine would minimize the distance between the track, possibly linearized over the cell distance, and the isochrone, by varying the track parameters. These include adjustments to the track vector in the WC4 chamber and adjusting the track position in PC1 and PC2 within limits allowed by the wire spacing in these chambers. The time-to-distance relation can then be iteratively corrected as in the trackfitting routine described above except that the corrections are performed per angular section per TDC bin. The advantages are two fold. The momentum of the track is found immediately. No complicated TDC calibrations have to be performed. Given enough data, the isochrones can be calculated from the residuals. Furthermore, the size of the look-up is reduced since the time-distance relationship is stored only for a relatively small number of angular sections.
Chapter 10

Summary and conclusions

The CHAOS detector requires a very low mass drift chamber that operates in weak and strong magnetic fields and which resolves the notorious left-right ambiguity for a large range of track incidence angles. It should have a small pitch yet a relatively uniform field and obtain an accuracy of 150 \( \mu \text{m} \) or better. The final WC3 prototype meets all of these requirements using a novel approach to solve the left-right assignments.

The first prototype chamber showed that the left-right ambiguity can be resolved for straight tracks passing to within 0.5 mm of the wire by reading either cathode strips or wires. A test in a 1 T magnetic field showed that the resolution is better than 150 \( \mu \text{m} \) over the whole drift space but the cathode strips and wires no longer provide information on the azimuthal position of the avalanche. The calibration chambers have a comparable resolution but provided useful left-right information from the diagonally opposed strips even at 1 T. The ratios of the induced charges on all surrounding strips indicated that the low field in the chambers allows the Lorentz force to carry the electrons to the far side of the sense wire.

The final prototype, designed to obtain a higher electric field, also provided experience with building a curved chamber and the use of crimp pins to string wires. The split cathode strips and larger anode wire diameter produce an electric field exceeding 1 kV/cm throughout the cell. The successful results from the August beam test clearly show that it is possible to resolve the left-right ambiguity in a drift cell of this geometry under the influence of a 1.6 T magnetic field by digitizing the induced pulse on only
two strips. As expected, this unique method achieves separation over a wide range of angles of incidence. Although no measurements were performed at lower magnetic field settings, simulations with the Garfield program indicate that $\Delta N_{lr}$, the normalized signal difference, will be reduced for the $-45^\circ$ tracks at lower field values. The separation for tracks from $0^\circ$ to $+45^\circ$ is less dependent on the Lorentz angle and is therefore expected to remain the same.

Both the MB43458 preamplifiers and the SL560 booster-inverter circuits successfully handle the high frequency wire pulses. The amplification does not significantly increase the signal noise but good grounding must be provided to reduce oscillations and pick-up. The combined system has sufficient gain to compensate for signal attenuation in the long (40 m) co-axial delay cables. The wide dynamic range of the 12 bit FASTBUS ADCs will handle the large range of signal height better than the 10 bit FERA ADCs used in the March and August beam tests.

The intrinsic resolution, $\sigma_x$, of the actual CHAOS WC3 chamber is expected to be below 150 $\mu$m but the calibration techniques must be further investigated. The effort should emphasize achieving accurate time-to-distance relations using Garfield. According to the results of De Boer et al. [29] (see section 5.1), the equations of motion for drift electrons can be corrected using two gas dependent parameters. The advantage of using Garfield is that the program could then calibrate the chambers for different magnetic field settings.

As a result of the experience with the final prototype the design for the CHAOS WC3 is now complete. The recommended drift cell has a 7.5 mm pitch, a half-gap of 3.75 mm, 50 $\mu$m anode wires, 100 $\mu$m cathode wires and 3 mm wide high voltage strips shared between adjacent cells. Several production questions do remain. The use of a low temperature solder paste is being investigated for soldering contacts on the very thin nickel-Kapton foils. Preliminary test show that the solder paste contacts are
strong and the heating process does not evaporate the nickel. Once mandrils become
available the rolling and glueing properties of Rohacell can be studied. High voltage
distribution boards have to designed. More recent Garfield calculations suggest that
the field shaping strips and the cathode wire can be operated at the same voltage (-600
V), reducing the number of separate high voltage cables.

Once the detectors are built and installed some beam time will be necessary to
determine the absolute positions of the chambers. It is proposed that the beam is aimed
through the spectrometer with the magnet off. If the chambers are built in separate
angular segments then data should be taken for various rotations of the spectrometer
to allow all the different sections to be covered by the beam. The trackfitting algorithm
discussed in Chapter 9 can be modified to fit straight tracks through all the chambers
and find chamber rotation and position offsets.
Bibliography

[6] All AutoCad diagrams were made by P. Amaudruz


[29] W. de Boer et al., *Nucl. Instr. and Meth.* 156 (1978) 249


[33] Chamber designed and constructed by P. Amaudruz


[37] Norman Wade Co., Vancouver, Canada.

[38] Sicom Industries, Surrey, Canada.


[40] Layout designed by P. Amaudruz

[41] H. Daum et al., *Nucl. Instr. and Meth.* 152 (1978) 541
Bibliography


[45] All Fujitsu MB43458 boards were designed by D. Maas, UBC Physics

[46] Data acquisition software by P. Amaudruz and R. Tacik


[48] Field map measured by summer student C. MacGowen

