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The OPAL Vertex Detector

by

J. Michael Roney

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

**Department of Physics
Carleton University
Ottawa, Ontario
February, 1989**

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Abstract

A high resolution charged particle tracking detector has been developed to measure vertex topologies of the subatomic particles produced in e^+e^- collisions of the OPAL experiment at LEP. The OPAL vertex detector is a 1 m long, 0.47 m diameter cylindrical drift chamber segmented radially into an axial and stereo layer each of which is divided into 36 'jet cells'. A prototype of the OPAL vertex detector containing 4 axial and 2 stereo cells was built to measure various characteristics of the detector design and to determine the limitations of spatial resolution in this design. It was studied using a pion test beam at CERN under a variety of operating conditions using two types of chamber gas.

The experiments with the prototype demonstrated that the detector drift time resolutions were limited mainly by chamber pulse non-uniformities. It is demonstrated that if a gas having a reduced drift velocity is used the design has the potential for obtaining resolutions better than $30\mu m$. A difficulty with a low velocity gas is that the electron drift velocity is strongly dependent on the applied electric field. A simple calibration technique that preserved most of the intrinsic resolution was developed by using a precise calculation of the electric fields in the detector together with a parameterized dependence of the drift velocity on the field. To obtain a coarse measurement of the coordinate orthogonal to the drift direction the difference in the arrival time of a pulse at opposite ends of each sense wire was used. It is shown that this technique is limited by signal-to-noise effects. Under optimal conditions the end-to-end time difference technique provided a measurement with a resolution of $100 ps$ which is equivalent to a spatial resolution of $2 cm$.

The OPAL vertex detector was built on the basic prototyped design with some modifications that would optimize the detector for operation with a low drift velocity gas. The results of the prototype studies were verified in early tests with the complete OPAL vertex detector.

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Chapter 1

Introduction

A high resolution charged particle tracking detector is necessary for the measurement of vertex topologies of particles produced in the e^+e^- collisions of the OPAL experiment at LEP. This thesis examines the requirements of such a 'vertex detector' and describes a set of experiments that have been performed as a means of developing a global understanding of the limitations of one particular detector design. It will be demonstrated that a drift chamber using a conventional jet cell geometry can be built having an intrinsic spatial resolution better than $30\mu m$.

The rest of this chapter develops the basic motivation for constructing this high resolution tracking detector. The role of the LEP accelerator in the quest for gaining an understanding of the fundamental processes in particle physics is discussed and the OPAL experiment is briefly described. Some of the fundamental particle physics problems that can be addressed using a vertex detector are briefly introduced at the end of this chapter.

A review of various vertex detectors in current use is presented in Chapter 2 as well as a discussion of the constraints for use of the particular designs. In the OPAL experiment a 1 m long, 0.47 m diameter drift chamber will serve as the vertex detector. It consists of an axial and stereo layer each of which is divided into 36 jet cells. Results of Monte Carlo studies that examine some aspects of the expected

performance of the detector in OPAL are presented in Chapter 2.

A prototype of the OPAL vertex chamber containing 4 axial and 2 stereo cells was constructed and studied using a 30 and 45 GeV pion beam at the CERN laboratory. The prototype studies were used to develop an understanding of the fundamental limitations to the intrinsic spatial resolution of this detector design. The design of the prototype detector is described in Chapter 3 and results of a Monte Carlo simulation of the detector used to investigate the expected intrinsic resolution are also presented there. The setup of the test beam experiments with the prototype and the results of studies investigating various aspects of the performance of the detector are presented in Chapter 4. Having established the intrinsic limitations, a variety of systematic effects that influence the absolute resolution of the detector were investigated. These are discussed in Chapter 5.

The prototype studies were subsequently used to guide the design of the complete 360° detector to be used in the OPAL experiment. The design modifications are presented in Chapter 6. Initial test data from this final detector became available at the time of writing this thesis and some preliminary results are also included in Chapter 6. Chapter 7 provides a general summary of the thesis as well as a discussion of potential improvements that can be made to the basic design of a minijet vertex chamber for use at OPAL.

1.1 e^-e^- Physics at the Z^0

The current understanding of the fundamental processes of particle physics is embodied in the *Standard Model* (SM)[1]. In this framework all *matter* is described in terms of elementary fermions, which are classified as either quarks or leptons, while the *interactions* between them are described in terms of the exchange of elementary bosons. The *electroweak* interaction is mediated by the photon, $W^\pm$ and the Z^0 gauge bosons while the *strong* interaction is mediated by *gluons*. All SM fermions

$$\begin{array}{l}
 \text{quarks} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \\
 \text{leptons} \quad \begin{pmatrix} e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}
 \end{array}$$

Figure 1.1: The Standard Model Fermion Generation Structure. The mass of each fermion generation increases from left to right.

exist in a mass hierarchy, or *generation*, structure (illustrated in Figure 1.1) and, as solutions to the Dirac equation, they all have anti-particle analogues. Both quarks and leptons interact electroweakly but what distinguishes them is that only the quarks also interact via the strong force. A significant consequence of the strong interaction is that individual quarks are not directly observed because they only exist in bound states referred to as *hadrons*. Hadrons are either bound states of a quark and an antiquark pair, called a *meson*, or a quark triplet known as a *baryon*. All directly observed strongly interacting subatomic particles are either baryons, (such as the proton or neutron), or mesons, (such as the pion or kaon).

The SM attempts to account for phenomena associated with the electroweak and strong interactions and thereby forms an underlying theory of atomic and nuclear physics. There is no known discrepancy between quantitative predictions of the SM and experimental data at the present time and it has been successful in making a variety of predictions in particle physics. However, although the SM has enjoyed tremendous success in providing an internally consistent theory of particle physics, it fails to predict the fermion generation structure, fermion masses and the relative strength of the different types of interactions between fermions. In addition, it is unable to quantitatively describe all aspects of the strong interaction and in particular does not address the process of hadronization which ensures that composite hadron particles, rather than quarks, exist in the final state of reactions

between fundamental fermions. Moreover, there remain two significant predictions of the SM which have yet to be experimentally verified. One is the existence of the t -quark¹, shown in Figure 1.1, and the other is the existence of the *Higgs* boson which is a by-product of the part of the theory that generates the mass of the $W^\pm$, Z^0 and fermions. Furthermore, the SM is unable to describe the electroweak and strong interactions within a single framework and does not address the questions of gravity at all. For these, and other reasons there has been great effort invested in looking beyond the SM for a more fundamental theory.

The experimental approach to the problem has been to search for deviations from the SM that could point the way towards that more fundamental theory. One of the consequences of the unification of the electromagnetic and weak interactions in the electroweak theory is that the relative strengths of the two interactions become comparable when the centre-of-mass energy of interacting fermions is approximately equal to the mass of the Z^0 , 92 GeV [3]. Because leptons do not interact strongly it has long been recognized that the annihilation of an electron-positron pair in this energy regime provides a valuable laboratory for experimenting with the electroweak sector of the SM. The SM cross section for

$$e^+e^- \rightarrow \text{Hadrons}$$

is plotted in Figure 1.2. At these energies the Z^0 is the dominant gauge boson involved in mediating the annihilation interaction. The annihilation produces an intermediate Z^0 boson state which then decays into a fermion-antifermion pair. All of the fermions listed in Figure 1.1 with mass less than approximately $M_z/2$ are copiously produced. If a quark-antiquark ($q\bar{q}$) pair is produced further strong interaction processes occur, sometimes referred to as hadronization, such that only the allowed composite hadron particles form in the final state of the reaction process. e^+e^- annihilation experiments at the Z^0 can address questions about properties of

¹The existence of the t -quark is not seriously in doubt because there is indirect evidence that suggests that its mass is less than 200 GeV assuming a three generation SM.[2]

Figure 1.2: The Cross Section for $e^+e^- \rightarrow \text{Hadrons}$

the gauge boson itself and, because of the large number of Z^0 bosons produced, questions pertaining to its decay and decay products can also be answered. Some of the questions that directly probe the SM and that can be addressed at the Z^0 are:

- Does the e^+e^- experiment confirm the existence of the Z^0 and if so is the SM adequate to describe its mass and width?
- What are the measured (i.e. model independent) cross sections of

$$e^+e^- \rightarrow f\bar{f}$$

for each f (i.e. fermion) species in this energy regime and are these measurements consistent with the SM?

- How many generations are there?

In addition, there are interesting questions that, although not providing a direct challenge to the SM, are ideally addressed at the Z^0 because of the high statistics

data that will be available and the higher energy regime that is accessible. For example:

- *Is there evidence for the existence of the t -quark, Higgs or magnetic monopole?*
- *What are the properties of the heavy quarks?*
- *What is an adequate description of the hadronization of quarks and gluons at these energies?*

If the energy of the e^+e^- interaction is increased by about a factor of two to the threshold of the reaction $e^+e^- \rightarrow W^+W^-$ then even more questions can be addressed.

- *Are the mass, width and branching ratios of the W boson consistent with the SM?*
- *What are the cross sections for $e^+e^- \rightarrow Z^0W^+W^-$ and $e^+e^- \rightarrow \gamma W^+W^-$?*

There are a variety of candidate theories that 'go beyond' the SM and which make different predictions that can be investigated in these energy regimes. Using these theories as a guide one naturally poses the question:

Is there evidence for particles or phenomena not predicted by the SM?

1.2 LEP

The value of experimentation at the Z^0 justifies the construction of an electron-positron colliding beam accelerator that can access this energy regime. Two laboratories have undertaken this task: SLAC (located near San Francisco, U.S.A.), which is now operating the SLAC Linear Collider (SLC). and CERN (located near

Figure 1.3: The LEP Ring.

Geneva, Switzerland), which is currently finishing construction of the Large Electron Positron Collider (LEP). LEP[4], pictured in Figure 1.3, is a conventional synchrotron in which electrons and positrons are accelerated and stored in counter rotating bunches. These beams are brought to a focus at four points around the accelerator. A detector is located at each of the four points and it is these detectors that measure the energy and momentum of the particles produced in the collisions of LEP.

As in all synchrotrons, the energy loss by synchrotron radiation varies as the fourth power of the $e^\pm$ beam energy and inversely as the radius. RF power is required to compensate for these losses. In the LEP design a compromise was made between its size and the installed RF power at a planned future Phase II maximum energy of 86 GeV. The result is that the main ring consists of four straight sections and four arcs with a bending radius of 3.099 km for a total 'circumference' of 26.66 km. At this circumference LEP is the world's largest synchrotron. Two of the straight sections are instrumented with a total of 16 MW of RF power. The beams intersect at eight points and will be brought to collide at four experimental

Final state fermion pair:	$\Gamma_{ff}/\Gamma_{\mu^+\mu^-}$
$e^+e^- \quad \mu^+\mu^- \quad \tau^+\tau^-$	1.0
$\nu_e\bar{\nu}_e \quad \nu_\mu\bar{\nu}_\mu \quad \nu_\tau\bar{\nu}_\tau$	1.9
$u\bar{u} \quad c\bar{c} \quad t\bar{t}$	3.5
$d\bar{d} \quad s\bar{s} \quad b\bar{b}$	4.4

Table 1.1: Ratio of Z^0 decay widths for e^+e^- annihilation to fermion-antifermion pairs at the centre-of-mass energy of the Z^0 peak to that of annihilation to $\mu^+\mu^-$ pairs. [1, eg:p159].

areas.

The electrons and positrons will counter circulate within the main ring's $13\text{ cm} \times 7\text{ cm}$ elliptical vacuum chamber in four pairs of bunches. For beam energies of 55 GeV the design calls for 4.2×10^{11} particles per bunch colliding every $22.2\text{ }\mu\text{s}$. When the beams are focused in the four experimental areas each beam will have a roughly Gaussian-elliptical transverse profile with $\sigma_{\text{horizontal}} \times \sigma_{\text{vertical}} = 310\text{ }\mu\text{m} \times 13\text{ }\mu\text{m}$ and a bunch length of 1.6 cm . The design luminosity² of the LEP beam will peak at a value of $10^{31}\text{ cm}^{-2}\text{s}^{-1}$ when the beam energy is 55 GeV but experimentation at lower luminosity will be possible up to 60 GeV .

The reaction cross section for muon production at the energy of the Z^0 peak is 5]

$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim 1\text{ nb}$$

after accounting for first order quantum electrodynamic radiative corrections. The ratios of the decay widths of the Z^0 of the four types of final state fermion pairs to that of $e^+e^- \rightarrow \mu^+\mu^-$ at the Z^0 energy as predicted by the SM are presented in Table 1.1. Summed over all final state fermions in a three generation Standard Model[6] with the top quark mass greater than $M_Z/2$:

$$\frac{\sigma(e^+e^- \rightarrow Z^0 \rightarrow X)}{\sigma(e^+e^- \rightarrow Z^0 \rightarrow \mu^+\mu^-)} \sim 29.$$

²Luminosity, as related to the physics of interest, is equal to the experiment reaction rate divided by the cross section.

For a luminosity of $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ these numbers translate into the production of roughly 0.32 Z^0 's per second or 28000 Z^0 's per day of accelerator operation. LEP is expected to reach this design luminosity during 1990 after obtaining 6 to 12 months of experience with the accelerator complex. To access the $W^\pm$ threshold a second phase of LEP is planned for the mid-1990s. This involves the introduction of superconducting RF cavities that will permit beam energies up to 100 GeV to be reached.

1.3 OPAL

A total of six experimental collaborations are expected to study e^+e^- physics in the energy region of the Z^0 . Two of these, Mark II and SLD, will share the single interaction point on the SLC³. The remaining four are at LEP (refer to Figure 1.3): ALEPH, DELPHI, L3 and OPAL.

The OPAL⁴ collaboration consists of roughly 200 physicists from 22 institutions in nine countries (see Table 1.2). The general philosophy of the collaboration[7] has been to provide a versatile and reliable detector that will be ready at the start of LEP running. A 'general purpose' detector which can investigate many problems simultaneously is necessary because of the wide range of unexplored physics at the Z^0 . To this end OPAL has endeavoured to provide a 4π detector that provides the following features:

- identification and measurement of the momenta of stable charged particles and photons up to the highest LEP energies.
- measurement of the total energy flow of all electromagnetic and strongly interacting stable particles.

³Mark II is currently running and will eventually be replaced with SLD.

⁴Omni Purpose Apparatus for LEP

Country	Institution	Main Responsibilities
Canada	Carleton	CD, Vertex
	Montreal	CD, Zed
	NRC	CD, Zed, Vertex
CERN	CERN	Magnet, CD, presampler endcap, beam pipe
France	Saclay	Data acquisition, TOF, Trigger
Germany	Bonn	CD, Jet
	Freiburg	CD, Jet
	Heidelberg	CD, Jet
Israel	Technion	Hadron endcap
	Tel-Aviv	Hadron endcap
	Weizmann	Hadron endcap
Italy	Bologna	Hadron barrel
Japan	Tokyo	E.M. barrel, Trigger, CD
United Kingdom	Birmingham	Muon endcap
	Cambridge	Vertex, E.M. endcap, Trigger
	Manchester	Muon barrel
	Queen Mary College	Vertex, E.M. endcap, Trigger
	R.A.L.	Vertex, E.M. endcap, Trigger
United States	University College	Forward
	Chicago	E.M. barrel presampler
	Maryland	Hadron barrel, beam pipe, forward
	Riverside	Hadron barrel

Table 1.2: The OPAL Collaboration

- the identification of short lived (i.e. picosecond) weakly decaying particles.

The collaboration achieves this goal by integrating a charged particle tracking spectrometer⁵ with a calorimeter⁶ and muon identifying system into the OPAL experiment. A cut-away diagram of the complete detector is presented in Figure 1.4.

e^+e^- collisions naturally lead to a cylindrical geometry and coordinate system for the detector. The coordinates used are z , for the distance along the OPAL beam pipe where $z = 0$ is at the average e^+e^- annihilation interaction point or *primary vertex*, ϕ , for the azimuthal angle and θ , for the polar angle. In addition, r , the radial distance from the beam is often used as well. This coordinate system is shown in Figure 1.5 and will be used throughout this thesis.

The spectrometer consists of a central tracking detector system (CD) located in a 0.4 *Tesla* magnetic field oriented parallel to the beam. The spectrometer magnet is a conventional solenoid with a soft steel yoke and pole tips for magnetic flux return. The solenoid, which wraps around the Central Detector pressure vessel, is 4 *m* in diameter and 6.5 *m* long. The Central Detector contains three separate drift chamber detectors placed in a common pressure vessel. The 'jet chamber'^[8], extending from an inner radius of 245 *mm* to an outer radius of 1850 *mm*, provides 159 $\frac{dE}{dz}$ samples⁷ with a high r - ϕ spatial resolution of approximately 130 μm and a coarse z measurement of approximately 4 *cm* from charge division. The momentum resolution of the Central Detector, $\frac{\sigma_p}{p}$, is expected to be $\sqrt{2^2 + (0.055 \cdot p_T(GeV))^2}$ %. The particle identification capability using the $\frac{dE}{dz}$ information has been measured in a prototype and has been shown to provide an electron-pion separation, $\frac{E_e - E_\pi}{\sigma_e}$, of 3.7

⁵A magnetic spectrometer determines the momentum of a charged particle by measuring the curvature of its trajectory in a magnetic field.

⁶A calorimeter is the term used in particle physics to describe a device that measures particle energies by absorbing the entire energy of the particle.

⁷Multiple sampling of the energy loss, referred to as (dE/dx) , of a charged particle as it ionizes a gas through which it travels depends on the velocity of the particle. This is combined with the spectrometer's momentum measurement of the particle to yield the particle's mass and hence its identity.

THE OPAL DETECTOR

- a) Vertex Detector
- b) Jet Chamber
- c) Z Chambers
- d) Magnetic Coil
- e) Preamplifier and Time-of-Flight
- f) Lead Glass Barrel
- g) Lead Glass Endcap
- h) Hadron Barrel
- i) Hadron Endcap
- j) Muon Barrel
- k) Muon Endcap
- l) Forward Detector

Figure 1.4: The OPAL Detector

Figure 1.5: The Coordinate System of the OPAL Experiment

at 6 GeV . Figure 1.6 displays the separation factor as a function of momentum for a variety of particle pairs as expected in the jet chamber. The 24 'Z-chambers'[9], which form a 4 m long barrel surrounding the jet chamber, provide six high resolution ($300\text{ }\mu\text{m}$) measurements of z and a coarse determination of $r\text{-}\phi$ (1 cm) from charge division. The beam pipe forms the inner part of the central detector 4 bar pressure vessel with the central section ($|z| < 155\text{ mm}$) having a radius of 79.4 mm and a thickness of 1.4 mm . The beam pipe consists of 1.3 mm of carbon fibre having a radiation length⁸ of 21.6 cm and a 0.1 mm aluminum liner for a total thickness of 0.71% radiation lengths. The 'vertex detector' occupies the region between the beam pipe and the jet chamber from an inner radius of 85 mm to an outer radius of 235 mm . This component fulfills several functions but the most significant is that it provides high spatial resolution tracking in $r\text{-}\phi$ which is used to assist in the identification of unstable particle decay vertices. The three CD detectors provide OPAL with the ability to identify and measure the momenta of stable charged particles

⁸The *radiation length* of a medium is defined as the distance travelled by a beam of electrons in the medium before the average energy of the beam has been reduced by a factor e through radiative losses.

Figure 1.6: Particle Separation in the OPAL Jet Chamber

and to identify short lived weakly decaying particles.

The 4 m long cylindrical magnetic spectrometer of OPAL is surrounded by barrel-shaped calorimeters and muon detectors. Calorimeters and muon identifiers also close off the ends of the detector down to $r \sim 54$ cm. The small angle conical volume between the endcap electromagnetic calorimeters and beam pipe is instrumented with a pair of forward detectors between $\theta = 45$ and 112 milliradians. Details of the OPAL subdetectors outside the Central Detector are discussed in Appendix A and the properties of all components are summarized in Table 1.3.

OPAL's response to e^+e^- events has been simulated using Monte Carlo calculations to assist in the design of various detector subcomponents and the physics analysis. The OPAL Monte Carlo computer program, *GOPAL*[65], is based on the CERN simulation package *GEANT*[11]. An example of the response of the various subdetectors to a 'typical' $e^+e^- \rightarrow c\bar{c}$ simulated event is presented in Figure 1.7.

Detector Component	Coverage	Main Characteristics
Beam pip.	79.4 mm radius for $ z < 155$ mm	1.3 mm thick carbon fibre pressure vessel wall
Vertex Cylindrical Drift Chamber	1 m long, $r_i = 85$ mm, $r_o = 235$ mm $\cos \theta < .95(.91)$ for 12 (6) axial (stereo) layers	axial: 12 radial of layers $50 \mu\text{m}$ resolution $r-\phi$ points 4° stereo: 6 radial layers of $720 \mu\text{m}$ resolution z points
Jet Cylindrical Drift Chamber	up to 4 m long, $r_i = 245$ mm, $r_o = 1850$ mm $\cos \theta < .73$ for 159 layers	159 radial layers of $130 \mu\text{m}$ resolution $r-\phi$ points with dE/dx , $\sigma_{PT} = \sqrt{2^2 + (0.055 \cdot PT (GeV/c))^2}$
Zed Planar Drift Chambers	4 m long, $r_i = 1880$ mm, $r_o = 1960$ mm $\cos \theta < .71$	6 radial layers of $300 \mu\text{m}$ resolution z points
Magnet	6.5 m long, 2 m radius	0.4 Tesla warm solenoid
T.O.F. Barrel	7 m long, $r = 2.3$ m, $\cos \theta < .84$	160 scintillators, βc measurement up to 2 GeV
E.M. Calorimeter	Barrel: 82% of 4π Endcap: 15% of 4π Forward: 2.9% of 4π	9440 22 X ₀ Pb-glass, pointing, intrinsic $\sigma_E = (4/\sqrt{E} + 1.5)\%$ larocci tube Presampler: 40% resolution recovery at 1 GeV 2x 1250 22 X ₀ Pb-glass, non-pointing, intrinsic $\sigma_E = 6/\sqrt{E}\%$ Pb-scintillator, intrinsic $\sigma_E = 17/\sqrt{E}\%$
Hadron Calorimeter	97% of 4π	iron yoke + larocci tubes: 1920 pointing towers $\sigma_E = 130/\sqrt{E}\%$
Muon Identifiers	Barrel: 70% of 4π Endcap: 15% of 4π	4 radial drift chamber layers of 1 mm resolution $r-\phi$ points outside 7.7 interaction lengths 2 x-y layers of larocci tubes with 1.5 mm resolution

Table 1.3: The OPAL Experiment: Characteristics of Detector Components

Figure 1.7: A Monte Carlo event display of an $e^+e^- \rightarrow c\bar{c}$ event in OPAL. The view is an r - ϕ projection onto the $z=0$ plane.

Particle	Lifetime (τ) (ps)	$c\tau$ (μm)
τ lepton	0.304	91.
$D^\pm$ charmed meson	1.069	320.
$D^0, \bar{D}^0$ charmed meson	0.428	128.
$D_s^\pm$ charmed meson	0.436	131.
Λ_c^+ charmed baryon	0.179	54.
$B^\pm, B^0, \bar{B}^0$	1.31	393.
unseparated beauty mesons		

Table 1.4: Lifetimes of short lived weakly decaying particles whose decay vertices can be used to assist in their identification[3].

1.4 Vertex Detection

Since the discovery of the J/ψ meson and charm quark in 1974 a number of short lived weakly decaying particles have been discovered. These particles have lifetimes between 10^{-13} and 10^{-12} s. The group includes the τ lepton and a variety of hadrons containing c (charm) or b (beauty or bottom) quarks. Their lifetimes (τ) and characteristic decay lengths ($c\tau$) are listed in Table 1.4.

The discoveries of these particles provided significant support for the Standard Model and experimentation with them at the energy of the Z^0 peak provides an excellent opportunity to challenge the SM. Many quantitative predictions of the SM can be investigated only if the identity of the primordial fermion-antifermion pair produced in the annihilation can be identified. This is a straightforward task when charged lepton pairs are produced: electrons, muons and taus are easily identified. However, the task of identifying the type (or ‘flavour’) of the primordial quark-antiquark pair in an $e^+e^- \rightarrow q\bar{q}$ event is non-trivial. In fact, it is virtually impossible to separate u , d and s quark events from each other because particles containing all of these are copiously produced in the hadronization process. On the other hand, the heavier quarks can only be produced in a decay of a quark more massive than itself or directly in the annihilation process. Therefore it is possible to identify

samples of events that have been enriched with charm or beauty and it is with these samples that much of the SM can be probed.

Some examples of the physics that can be studied once enriched samples of the c and b quark events are available include:

- Measuring the branching ratios of $Z^0 \rightarrow c\bar{c}$ and $Z^0 \rightarrow b\bar{b}$
- Measuring the forward-backward asymmetries of $Z^0 \rightarrow c\bar{c}$ and $Z^0 \rightarrow b\bar{b}$
- Studying the hadronization of c and b quarks.
- Searching for the t quark via its decay to beauty.
- Searching for the Higgs which preferentially decays to the heaviest kinematically allowed fermion-antifermion pair.
- There are a large number of physics problems associated with b-quarks that are ideally addressed at LEP because of their copious production at the energy of the Z^0 peak. These topics include determination of elements in the Kobayashi-Maskawa mixing matrix, studies of B^0 - $\bar{B}^0$ mixing, particle spectroscopy, masses and lifetime measurements.

There still remains the experimental problem of identifying c and b quark events. Charmed and beauty hadrons can sometimes be identified as peaks in the invariant mass plots of subsets of the particles observed in a detector provided the combinatorial background is not too severe. But a very powerful quark identification tool lies in the fact that these particles have a lifetime that permits them to travel measurable distances before they decay. If the individual tracks of detected charged particles can be associated with the decay vertex of one of these unstable particles then this information can be used to reduce the background.

The vertex detector performs the task of associating particular tracks with secondary vertices that are separated from the primary vertex. Examples of typical

Figure 1.8: Examples of vertex topologies in e^+e^- annihilation to (a) τ leptons, (b) charm and (c) beauty quarks at the energy of the Z^0 peak.

vertex topologies in e^+e^- annihilation to τ leptons, charm and beauty quarks are presented in Figure 1.8. Because these particles decay inside the beam pipe only the tracks of the stable charged decay products are observed in the vertex detector. Figure 1.9 is an Monte Carlo generated example of what the OPAL vertex detector would detect in a typical $e^+e^- \rightarrow c\bar{c}$ LEP event at the energy of the Z^0 peak. The mean number of charged particles produced in a hadronic event is approximately 20.

A tracking detector that has a high spatial resolution and that is located close to the annihilation point can identify tracks that do not originate from the primary

Figure 1.9: Examples of charged tracks in the OPAL vertex detector region originating from an $e^+e^- \rightarrow c\bar{c}$ event at a centre-of-mass energy of 93 GeV . This is a projection onto the XY plane at $Z=0$ and was generated by the OPAL Monte Carlo simulation program, GOPAL.

vertex. The simplest way of doing this is to measure the tracks' impact parameter (δ), or distance of closest approach, to the primary vertex. The impact parameter is explicitly shown for one of the tracks in Figure 1.8. Particles produced in the decay of a charmed or beauty hadron on average have larger impact parameters than particles produced at the primary vertex. By measuring the impact parameters of the tracks in the event a vertex detector can assist in separating charmed and beauty events from each other and from events in which the lighter quarks are produced directly in the annihilation.

An estimate of the magnitude of the impact parameter for the various particles listed in Table 1.4 can be obtained by recognizing that the angle, ψ , between the momenta of daughter and parent particles is approximately equal to the ratio of the impact parameter to the flight path of the parent. A characteristic flight path of the parent is:

$$v\tau = \frac{p}{m}\tau = \beta_{\text{parent}}\gamma_{\text{parent}}c\tau$$

so

$$\psi \sim \frac{\delta}{\gamma_{\text{parent}}\beta_{\text{parent}}c\tau}$$

A characteristic value of ψ in particle decay is

$$\psi \sim \frac{\beta_{\text{daughter}}^{\text{rest frame}}}{\beta_{\text{parent}}\gamma_{\text{parent}}}$$

and because $\beta_{\text{daughter}}^{\text{rest frame}} \sim 1$ a characteristic value of the impact parameter is

$$\delta \sim c\tau.$$

The interesting aspect of this is that although the decay lengths of τ , c and b increase as the momentum of the particle increases, the impact parameters of their daughters is approximately the same because the decay angle becomes smaller. Therefore estimates of the impact parameters are provided by the values of $c\tau$ listed in Table 1.4.

The situation for beauty is complicated by the fact that hadrons containing the b quark usually decay to charmed hadrons and other non-charmed charged particles. As a result the vertex topology of beauty decays is more complex because it consists of five vertices in total compared to three for charm. The subsequent decay of the charmed particles results in an increase in the average impact parameter. For these reasons there are more tracks with large impact parameters in $e^+e^- \rightarrow b\bar{b}$ events than in $e^+e^- \rightarrow c\bar{c}$ events. Because of this and the fact that b hadrons have decay lengths much greater than those of c hadrons the efficiency for identifying beauty events using the vertex topologies is significantly higher than for charm.

A number of detector technologies have been used to perform vertex topology measurements. The details of various experimental constraints significantly affects the choice and performance of a particular type of vertex detector and the method used to measure vertex topologies. These are considered in Chapter 2.

The design of the OPAL vertex detector is influenced by the constraints of the e^+e^- experiment. The detector is a mini-jet cylindrical drift chamber that will be operated at 4 bar pressure. The detector was designed primarily to provide high resolution tracking in $r-\phi$ for use in the measurement of vertex topologies. In addition, however, a coarse vertex z measurement is made using end-to-end timing for use in the OPAL trigger and for initial pattern recognition. A high precision z measurement using a layer of stereo wires is also provided as a means of improving the measurement of the polar angle of tracks. This significantly improves the momentum and mass resolution of short lived particles such as neutral kaons. Details of the design and examinations of its performance are presented in this thesis.

Chapter 2

Vertex Detector Physics

The principle role of a vertex detector is to provide very high resolution tracking measurements as close to the interaction point as possible. With these measurements the topologies of the vertices in the interaction may be examined and used to provide information associated with the lifetimes of the particles produced. A review of various vertex detector designs currently in use in particle physics experiments is presented in Section 2.1. Included in their description is a very brief review of some physics measurements performed with the aid of these devices.

The vertex detector at OPAL has been designed to serve three functions. In addition to vertex information, the detector provides a good measurement of the z coordinate (resolutions of the order of a millimetre) of the tracks near the interaction point using a stereo cell system. By combining the stereo cell z measurement with a $300\mu m$ resolution measurement of z at a distance of 2 m from the interaction point (provided by the OPAL Z-Chambers) an excellent measurement of the θ angle can be made. This gives a significant improvement in the measurement of the masses of particles such as the K_J^0 . Thirdly, a coarse measurement of the z position of hits using a time-difference measurement is to be used in the OPAL hardware event selection or 'trigger'. This vertex R-Z component of the OPAL trigger is intended to reject events having an interaction vertex outside of the e^+e^- interaction region.

In this way, many of the non-annihilation interactions, such as interactions between the beam and residual gas molecules inside the beam pipe, can be identified and rejected. The contributions of the vertex detector to each of these three areas will be reviewed in this chapter.

2.1 Review of Vertex Detectors

Vertex topologies have been studied using a variety of techniques in different types of particle physics experiments. Usually the particular constraints of a given experiment have determined the most appropriate technique. In particular, 'fixed target' experiments do not have the same constraints as 'colliding beam' experiments.

2.1.1 Hybrid detectors

The main considerations when choosing a vertex detector for a fixed target experiment include the response of the detector to high radiation doses and whether or not the device has electronic readout. The experiments exhibiting the highest vertex resolution have been 'hybrid emulsion spectrometers' which integrate a spectrometer system with a nuclear emulsion vertex detector. Although their use is restricted to relatively low radiation rate environments to prevent overexposure of the emulsion, the high intrinsic spatial resolution of nuclear emulsions¹ has permitted these detectors to make precision charmed hadron lifetime measurements in fixed target experiments [12,13]. The necessity of employing visual scanning techniques to analyze the vertex information together with the 'low rate' restriction mentioned above renders the hybrid emulsion spectrometer an inappropriate detector in high statistics experiments (i.e. experiments that collect many events). Despite this drawback, this technique continues to provide interesting physics results that are available in advance of higher statistics experimental measurements. For example,

¹Flight paths have been measured with a resolution as fine as $1\mu m$ [12].

a difference between the lifetimes of charged and neutral beauty hadrons has until now only been examined in a hybrid experiment[14].

A variation on the nuclear emulsion theme is the use of a high resolution bubble chamber with a spectrometer. With the rapid cycling (typically 30 Hz) of a small bubble chamber, tracks consisting of $20\mu m$ diameter bubbles can be generated. This translates into a single measurement precision of approximately $2\mu m$ and a two track resolution of $20\mu m$ [15]. Such a device has been used to provide samples of charm having less than a 1% background by using vertex topology information[15]. However, like the hybrid emulsion spectrometers, the visual scanning process prevents these devices from being used in high statistics experiments. For example, the above mentioned clean charm sample size is 25 events.

2.1.2 Semiconductor detectors

Because hybrid detectors are inappropriate in high rate environments semiconductor detectors are currently the favoured method for vertex detection in fixed target experiments. These have the distinct advantage of providing both very high resolution and digital readout. A semiconductor detector is fundamentally a reverse-biased junction that senses the electronic signal produced when ionizing radiation generates charge within the junction's depletion region. The high resolution may be provided by several methods. In 'silicon strips' one side of the junction is instrumented with a series of narrow conducting readout strips. The spatial resolution obtained with these devices is typically between 10 and $20\mu m$ and is determined by the size and spacing or 'pitch' of the strips (generally between 20 and $50\mu m$). A 'charged coupled device' or CCD has a two dimensional system of potential wells which hold the charge until the device is readout. The spatial extent of the wells determines the resolution of such detectors. Resolutions as high as $5\mu m \times 5\mu m$ have been achieved in a running experiment 16. A description of the operation of

various solid state vertex detectors is reviewed in Reference [17].

Examples of the physics that is accessible in fixed target experiments using silicon strip vertex detectors are provided by the results of the Tagged Photon experiment (Fermilab E691) at the Fermilab accelerator laboratory near Chicago, U.S.A.. E691 has provided definitive high statistics measurements of the lifetimes of charmed hadrons[18]. Also, by using its ability to identify charm mesons with the vertex information, this experiment has set the current best limit on the mixing of the D^0 and $\bar{D}^0$ mesons[19] and has provided measurements or set limits on a number of charmed meson decays[20]. In effect, by using the lifetime tag, all studies of the physics of charmed particles have been made accessible with minimal background.

The first experiment to use a CCD vertex detector was the ACCMOR collaboration at CERN (CERN NA32). This experiment has also provided measurements of charmed hadron properties. In particular, it has provided an excellent measurement of the mass and lifetime of the Λ_c^+ baryon[16].

Although solid state devices will eventually be introduced into MARK II, ALEPH and DELPHI, this promising technology has yet to be used in a colliding beam experiment.

2.1.3 Drift chambers

In the collider environment the only vertex detectors used to date have been based on the drift chamber and generally have lower intrinsic spatial resolution than the detectors previously mentioned. At the fundamental level a drift chamber is a proportional counter in which the drift time of the electrons produced by ionizing radiation is measured.

The classic proportional counter is simply a gas filled conducting cylinder with a wire strung along its axis. A potential difference is applied between the wire, which

forms the anode, and the cylinder to generate a large electric field on the surface of the anode². When an ionizing particle traverses the gas electron-ion pairs are produced along the particle's trajectory³. The liberated electrons are attracted to the anode and in the high field region near the anode they gain sufficient energy to further ionize the gas. The newly released electrons also accelerate in the field, further ionize the gas and ultimately generate an avalanche of electron-ion pairs within a few wire radii of the anode. The electron avalanche is collected at the sense wire and, as the ions drift away from the anode, a measurable signal is produced on the wire. With an appropriate anode surface field the amplitude of the gas-amplified signal is proportional to the initial number of electron-ion pairs.

In a *drift chamber* a low electric field⁴ is established throughout most of the detector volume. The electrons produced from the initial ionization drift in the low field towards the anode. On arriving at the anode an avalanche forms and a signal is produced. The time elapsed between the passage of the ionizing particle and the detection of the chamber signal is measured using a 'time-to-digital converter' or TDC. Provided the drift time-to-distance relationship is known, this time provides a measure of the position of the particle when it traversed the chamber. In practice a drift chamber consists of numerous 'drift cells' each of which has its own anode wire and which operates in the manner described above.

The time-to-distance relation of a chamber and the precision with which the measurement can be made is dominated by the transport properties of the ionization electrons as they drift in the electric field. These properties depend on the gas, pressure, temperature and electric field. In general, the field should be as uniform as possible, the pressure above atmospheric, and the temperature should

²The anode surface field, E_a , is typically of order of a few 100 kV/cm at 1 bar pressure. The actual value depends on the desired gas gain, the gas filling the detector and wire diameter.

³In an argon-based gas approximately 100 electron-ion pairs/cm are produced at atmospheric pressure.

⁴Typically of the order of 1 kV/cm at 1 bar pressure.

be constant. The choice of gas is determined, to a large extent, by how well the above conditions can be met. These issues will be discussed in some detail in the following chapters and Appendix B. In brief, ‘hot gases’ generally exhibit intrinsic spatial resolutions that are limited by the timing electronics and electron diffusion. ‘Cool gases’ can provide higher resolutions as long as the above listed systematics are strictly controlled or well understood. A review of the various factors that potentially influence the resolution of high resolution drift chambers is presented in Reference [21]. The constraints imposed on drift chamber designs for use at e^+e^- colliders are not always consistent with optimal resolution and the challenge has been to attain the highest resolution while working within these constraints.

2.1.4 Vertex drift chambers at e^+e^- colliders

Invariably, the main charged particle tracking of the collider spectrometers has been provided by large volume drift chambers which possess space resolutions that approach $150\mu m$ [22]. Vertex detection physics studies require higher spatial resolution measurements located near the interaction point. Because these measurements are difficult to perform in large volume detectors, smaller detectors optimized for high spatial resolution have been developed and have been placed around the beam pipe inside the main tracking chamber.

The geometry in the collider environment has forced all of these to have the same basic cylindrical shape with the wires oriented parallel to the beam pipe. This means that the high resolution measurement is made in the plane perpendicular to the beam (the $r-\phi$ plane). Accessing information about the coordinate of a hit along the beam (i.e. the z component) until now has generally been handled outside the vertex detector.

The physics measurements that have been significantly improved using the collider vertex detectors include lifetimes of the τ [23] and beauty hadrons[24]. The

charm lifetime measurements are still performed in these experiments but the earlier measurements have now been entirely dominated by the higher precision, high statistics fixed target experiments.

The collider vertex detectors are also used in the experiments to reduce the combinatorial backgrounds. These arise when all possible combinations of particles are separately hypothesized to be the decay products of a parent particle under study. Since the parent may decay into only one of the many hypothesized combinations the wrong combinations form a background. If vertex information is available then many of the wrong hypotheses can be rejected on the basis of improbable vertex topologies. In ARGUS for example, the vertex detector is used to improve the reconstruction efficiency and signal-to-background of K^0 and Λ particles[25].

Cell-based vertex detectors

All existing collider vertex drift chambers may be classified as either 'cell' or 'jet' based. In the cell based detectors individual anode wires are surrounded by a cathode formed either by wires as in the ARGUS[26] design or an aluminized mylar tube as in the MAC[27] or MARK III[28] designs. The cell size in the vertex detectors of this design has an inscribed radius of several millimetres. The electrostatic field in this design is similar to that of the classic proportional tube. It varies inversely with distance from the wire and therefore tends to require nonlinear time-to-distance relations for high resolution use. The greatest advantage of this design is its simplicity of implementation. Mean resolutions as good as $40\ \mu\text{m}$ have been reported with this design when operated at 4 bar pressure and gas gains of in excess of 10^6 [27].

Minijet vertex detectors

The anode wires in jet based drift chambers are aligned in a plane located between two planes of cathode wires. The 'jet cell' geometry is based on a tapered wedge of a cylinder with sets of electrodes closing off the inner and outer radii. The maximum drift lengths in minijet vertex detectors are determined by the distance between the anode and cathode planes and typically range between 1 cm to 5 cm. Most of the space between the anode and cathode planes has a relatively uniform electrostatic field referred to as the 'drift field'. Near the anode wires the field increases and approaches that of a proportional counter.

Classic Jet Chambers In these versions of the minijet detectors an additional wire is placed between adjacent anode wires. These 'guard' or 'potential' wires provide several functions. The principle function is to reduce cross talk between adjacent anodes. When the positive ions move away from an anode wire a positive pulse is induced on all neighboring electrodes (in addition to the negative polarity signal on the anode wire itself). The signal induced on neighboring anode signal wires is minimized by placing a larger diameter 'guard' wire between anode wires. Secondly, the voltage applied to these wires can be used to tune the electrostatics of the detector, which is the reason these wires are often referred to as 'potential wires'. They can be operated with cathode-like surface fields to increase the electric field at the surface of the anode and thus increase the gas gain. Alternatively they can be operated with anode-like surface fields to reduce the gain. The details of the drift field are also influenced by this fine-tuning and can be used to optimize the electron arrival time distributions⁵. Finally, because these wires are the closest to the sense

⁵Ideally a uniform electron arrival time distribution is desired but electrons generated by ionization located near the edge of the anode wire sampling slice travel further than those produced at the middle of the slice and therefore they arrive later. When operated with a cathode-like field the field lines near the anodes are pushed away from the guard wires thus forming a 'wine bottle' shape. This tends to decrease the distance travelled by the electrons produced at the edge of the sample and improves the uniformity of the electron arrival times. If an anode-like surface field is placed

wires, they form the dominant return current path in the signal transmission to the end of the wire where the first stage of electronics amplification occurs.

Only at JADE has a classic jet design been employed as an operating vertex detector in an e^+e^- experiment[29]. Resolution and physics results using that detector have yet to be published.

The OPAL vertex detector design is a scaled down version of the classic jet chamber. The various constraints on the design, which are discussed in detail in Chapter 3, have been imposed to permit the detector to be operated with good resolution (approximately $60\mu m$) in a hot gas. However, it will be demonstrated in the following chapters that the design is also well suited for operation with a cool gas and that resolutions as low as $25\mu m$ can be obtained.

Time Expansion Jet Chambers A more complex version of the jet cell places a complete grid of wires between the anode and cathode planes. The grid wires are located a few millimetres from the anode plane. In these 'time expansion chambers' (TEC) the grid separates the cell into a drift and gain region. With the additional electrodes a very uniform drift field can be established between the grid plane and cathode. Anode surface fields can be tuned independently of the drift field and with appropriate tuning of the guard wire potentials, the isochrones can be made quite uniform. In practice, the TEC requires a minimum distance between the grid and cathodes of several centimetres[30,31,32]. This is an ideal design where long drift lengths form a design criterion⁶. However, for a vertex detector operating with a gas that has non-negligible diffusion characteristics the drift length is a parameter that is generally minimized.

on the guard wires the anode field decreases because the field lines terminating on the cathodes are shared between anodes and guards. As a consequence, the anode sampling width is decreased. The electron arrival times of a decreased sample width are more uniform because late arriving electrons (or, more precisely, what would have been late arriving electrons) now end up on the guard wires.

⁶This is the basic design used in the OPAL ZED Chambers which have a maximum drift length of 50 cm [9].

The only experiment that has used this design in a working vertex detector, MARKJ[31], used a cool gas ($\text{CO}_2(80\%)\text{-isobutane}(20\%)$). With a mean grid-cathode gap of approximately 2 cm, an outstanding mean spatial resolution of $40\mu\text{m}$ was achieved. There are two groups (MARKII and L3) that have designed and built TEC vertex detectors to be used for physics at the Z^0 energy region.

2.2 Vertex Topology Measurements

Experimental identification of the hadrons containing charm or beauty quarks has historically been accessible only through the presence of peaks in the invariant masses of various combinations of observed final state particles. Such a technique introduces a background associated with the choice of wrong combinations of observed particles in the reconstruction of the parent. If an event has many final state particles this 'combinatorial background' becomes a significant impediment to the study of the physics associated with the parent particle.

The combinatorial background in charm and beauty quark studies can be significantly decreased simply by identifying events that have secondary vertices in the region of the primary interaction point. These additional vertices indicate the presence of a very short-lived parent particle independent of consideration of the invariant masses. It is the combination of the identification of a sample of events having secondary vertices and the measurement of invariant masses in those events that provides the cleaner sample of τ leptons and c and b hadrons. A more detailed examination of the topology of the interaction region of an event introduces the opportunity to associate observed tracks with a secondary vertex. In this way the number of combinations of final state particles used in the mass reconstruction is vastly reduced and the cleanliness of the sample of the parent particles dramatically improved. The ability to associate tracks with the correct vertices requires extremely high spatial resolutions and is the driving force in the current quest for

high performance vertex detectors.

The tools that are developed for identifying secondary vertices can also be used for the measurement of the lifetime of the parent particles. The lifetimes of the τ lepton and individual charmed hadrons have now been reliably measured and no significant improvement on these measurements is expected at LEP. In the case of hadrons containing beauty, however, lifetime measurements can be significantly improved at the LEP experiments.

The principal tool that will be used is the impact parameter of the charged particle tracks. As described in Chapter 1 tracks of secondary decay products will not intersect the primary vertex but will have a finite impact parameter. The precision of impact parameter measurement depends strongly on the momentum of the tracks because of multiple Coulomb scattering effects: particles with low momentum will have poorly measured impact parameters. This dependence is discussed in Section 2.2.2. The efficiency of tagging a quark using the vertex detector therefore depends on the momentum distribution of all particles produced in the event.

2.2.1 Impact parameters and momentum distributions

To gain some insight into the nature of this complex problem of quark tagging using track impact parameters the expected momentum distributions and impact parameters of particle tracks in hadronic events were calculated using the OPAL Monte Carlo simulation program GOPAL116. With this program three equal data sets of $(e^+e^- \rightarrow s\bar{s})$, $(e^+e^- \rightarrow c\bar{c})$ and $(e^+e^- \rightarrow b\bar{b})$ hadronic events were generated at $\sqrt{s} = 93\text{GeV}$ using the LUND fragmentation model. The default parameters of LUND 6.3 were used and are listed in Reference [33]. The heavy quarks were decayed in GOPAL using the lifetimes published in Reference [3].

The momentum distributions are presented in Figure 2.1. A dominant feature of these distributions is the fact that nearly half of the particles have momenta less

than $1 \text{ GeV}/c$ and the proportion of particles with momenta greater than $10 \text{ GeV}/c$ is approximately 3%. Another general feature of these distributions is that as the mass of the primordial quark increases the average momentum of particles in the event decreases. A particle with low momentum will not have a high precision impact parameter measurement and therefore the task of tagging quarks based on lifetimes will depend on a very small proportion of the higher momentum tracks for which the impact parameter is significantly separated from the primary vertex.

The effects of the large number of low momentum tracks and multiple scattering are quite evident in plots of the r - ϕ impact parameters of charged tracks in the $(e^+e^- \rightarrow s\bar{s})$, $(e^+e^- \rightarrow c\bar{c})$ and $(e^+e^- \rightarrow b\bar{b})$ hadronic events. These impact parameters were obtained after fitting circles to the tracks in the simulation. In Figure 2.2 the impact parameters of all charged tracks have been included. Even $s\bar{s}$ events which have very few secondary vertices have a large number of tracks with impact parameters greater than the $c\tau$ of charmed hadrons. These large impact parameters are associated with the scattering of low momentum particles. This is evident when only the impact parameters of particles having a transverse momentum greater than $5 \text{ GeV}/c$ are used (see Figure 2.3). The ability to use vertex information to help identify heavy quark events is also evident from the plots shown in Figure 2.3. In order to take advantage of the vertex information, however, it is essential that the momentum dependence of the impact parameter resolution be well understood so that an appropriate weighting of the impact parameter measurements can be applied in any quark tagging scheme that is used.

2.2.2 Impact parameter resolutions

The resolution of the impact parameter is influenced both by the multiple scattering through the beam pipe and various detector materials as well as the intrinsic reso-

Figure 2.1: Momentum distributions of charged particles produced in Monte Carlo generated ($e^+e^- \rightarrow s\bar{s}$), ($e^+e^- \rightarrow c\bar{c}$) and ($e^+e^- \rightarrow b\bar{b}$) hadronic events at a centre-of-mass energy of 93 GeV.

Figure 2.2: Impact parameters of all charged tracks in Monte Carlo generated ($e^+e^- \rightarrow s\bar{s}$), ($e^+e^- \rightarrow c\bar{c}$) and ($e^+e^- \rightarrow b\bar{b}$) hadronic events at a centre-of-mass energy of 93 GeV.

Figure 2.3: Impact parameters of charged particle tracks with transverse momentum greater than $5 \text{ GeV}/c$ from Monte Carlo generated ($e^+e^- \rightarrow s\bar{s}$), ($e^+e^- \rightarrow c\bar{c}$) and ($e^+e^- \rightarrow b\bar{b}$) hadronic events at a centre-of-mass energy of 93 GeV .

lution of the detectors. The OPAL Monte Carlo program, GOPAL114⁷, was used by Routenburg[34] to investigate the r - ϕ impact parameter (d_0) and momentum (p) resolutions of muon tracks generated at the origin and ranging in momentum between 0 and 50 GeV/c. The tracks were fitted in the r - ϕ plane using a circle fit to all points in the central detector. Plots of these resolutions as a function of momentum and OPAL vertex detector resolution are presented in Figure 2.4. The resolution of the OPAL Jet Chamber points were held constant at $130\mu m$. The significance of the multiple scattering at low momentum is quite evident in these plots as is the importance of the vertex detector measurements.

Using this study of the d_0 impact parameter resolution a parameterization was developed that modelled various contributions to the d_0 resolution:

- Intrinsic resolution of d_0 . This is approximately proportional to the vertex detector point resolution when the jet chamber resolution is held fixed at $130\mu m$. (C_1 term)
- Multiple scattering in the vertex detector gas. (C_2 term)
- Multiple scattering in the jet chamber gas. (C_3 term)
- Multiple scattering in non-gaseous central detector media such as the beam pipe. (C_4 term)

The resolution was parameterized as:

$$\sigma_{d_0} = \sqrt{\sigma_{VXD}^2 \left(C_1^2 - \frac{(C_2 \times P)^2}{p^2} \right) + \frac{(C_3 \times P)^2 + C_4^2}{p^2}} \quad (2.1)$$

⁷ GOPAL 65 is the OPAL Monte Carlo computer program that uses the CERN simulation package GEANT11. Particles are tracked through the material of the OPAL detector taking into account all significant interactions (decays, multiple scattering, etc.).

Figure 2.4: r - ϕ Impact parameter Resolutions as a Function of Momentum and OPAL Vertex Detector Resolution. This figure is from Reference [34].

σ_{VXD} (μm)	Momentum (GeV/c)			
	2.5	5	10	20
20	104	52	27	15
40	110	57	31	20
60	121	63	37	26
80	134	71	43	33
100	149	81	51	40
130	174	96	63	51

Table 2.1: $r - \phi$ impact parameter resolution in microns for various σ_{VXD} . (OPAL jet chamber resolution = $130 \mu m$).

where:

$$\begin{aligned}
 C_1 &= 0.3571 \\
 C_2 &= 0.6443 \frac{\text{GeV}/c}{\text{bar}} \\
 C_3 &= 33.15 \frac{\mu m \cdot \text{GeV}/c}{\text{bar}} \\
 C_4 &= 215.6 \mu m \cdot \text{GeV}/c
 \end{aligned}$$

σ_{VXD} is the mean resolution of a single vertex detector point, P is the OPAL central detector gas pressure and p is the momentum of the particle. With these values of the parameters there is better than a $1 \mu m$ agreement between the parameterization and Figure 2.4 at both 5 and 10 GeV/c. For momenta below 5 GeV/c the parameterization is a valid description of the Monte Carlo at the the 10% level.

This parameterization clearly shows the relative influence of the various components on the resolution of d_0 . The contribution of a high resolution vertex detector to the impact parameter measurement can be assessed by comparing σ_{d_0} for various values of σ_{VXD} to σ_{d_0} for $\sigma_{VXD} = 130 \mu m$ (the resolution of the OPAL jet chamber). σ_{d_0} is presented as a function of momentum for a range of values of σ_{VXD} at a pressure of 4 bar in Table 2.1. When the resolution of the vertex points is less than $50 \mu m$ the resolution of the impact parameter for tracks with momenta greater than 10 GeV is more than a factor of two better than if the vertex points had the same resolution as the OPAL jet chamber.

Scattering in the gas provides a non-negligible degradation of the resolution, as can be seen from the pressure dependent terms. This suggests that if a scheme that

Momentum (GeV/c)	Billoir P=4.0 bar	Circle Fit Parameterization	
		P=0.0 bar	P=4.0 bar
1	181	216	284
2	105	109	143
4	65	57	73
5	54	47	60
10	34	28	34
15	29	23	26

Table 2.2: r - ϕ impact parameter resolution in microns using the Billoir fitting method with $\sigma_{VXD}=50\mu m$ and $P=4\text{ bar}$ and as calculated using Equation 2.1 with $P=0\text{ bar}$ and $P=4\text{ bar}$.

accounts for multiple scattering in the gas is adopted in the fitting procedure an improvement in impact parameter resolution is likely. One such method has been developed by P. Billoir[35]. This is a recursive technique that starts the fit using points at the outer radius of the detector. At each step a point closer to the vertex is added and the fit is updated. The multiple scattering is accounted for by adding the average scattering angle to the error matrix of the track parameters as each new point is added to the fit.

A GOPAL Monte Carlo study of impact parameter resolutions in the OPAL detector using the Billoir method was performed by Batley 36. The impact parameter resolutions using this method are tabulated in Table 2.2 along with the value of σ_{d_0} calculated using Equation 2.1 with the pressure, P , set to zero which provides an estimate of the potential improvement that can be gained using a technique that minimizes multiple scattering contributions to σ_{d_0} . The entries in this table demonstrate that within the 10% uncertainty of the values below $5\text{ GeV}/c$ the Billoir fit provides the same impact parameter resolution as the circle fit would if there was no gas in the detector. This represents an improvement of between 30 and 40% for particles with a momentum of 2 GeV .

If the pressure dependent terms are neglected, one is still left with a momentum dependent term that originates from multiple scattering in the beam pipe and other

non-gaseous detector materials. The contribution of scattering in the beam pipe can be calculated using

$$\sigma_{d_0}^{BP} = \sigma_0 \times (\text{beam pipe radius})$$

where[37]:

$$\sigma_0 = \frac{14.1 \text{ MeV}/c}{p\beta} Z_{inc} \sqrt{L/L_R} [1 + \frac{1}{9} \log_{10}(L/L_R)] (\text{radians}) \quad (2.2)$$

Insertion of the beam pipe radius and number of radiation lengths, L/L_R , of the beam pipe (7.94 cm and 0.0071 respectively) into this expression yields a contribution from the beam pipe of $72 \mu\text{m} \cdot \text{GeV}/c$. A comparison of this with the $215.6 \mu\text{m} \cdot \text{GeV}/c$ from the parameterization of the Monte Carlo simulation indicates that the pressure independent multiple scattering contribution is *not* dominated by scattering in the beam pipe. The only other major scattering interface in the central detector is the vertex detector's outer carbon fibre tube⁸. This is 1.5 mm thick and has a radius of 235 mm. From this simple analysis it would seem that a fitting procedure that takes into account scattering at the vertex detector's carbon fibre interface may have the potential for improving the impact parameter measurement.

2.3 The Momentum Measurement

In addition to the impact parameter the vertex detector points contribute to the momentum resolution. Using the Monte Carlo scheme described above, the momentum resolution measurements have been simulated with a vertex resolution of $70 \mu\text{m}$ and with the vertex points effectively removed from the fit[34]. The plots of

⁸This assumes that scattering associated with the wires does not contribute significantly to the impact parameter resolution as calculated in this study. This is a fair assumption because a jet chamber has the wires aligned along various radii which introduce effectively no material for almost all tracks. The few particles that do interact with the wires would contribute to the tails of the impact parameter distribution. Since the resolutions used here are gaussian fits to the distributions, which are relatively insensitive to tails, it is fair to assume that the wires contribute negligibly to the resolution used in this study.

momentum resolution with and without vertex points are presented in Figure 2.5, which is taken from Reference [34]. From these plots it is clear that the vertex points improve the momentum resolution for momenta greater than 15 GeV/c.

2.4 The θ Measurement

The combination of the stereo part of the vertex detector and the OPAL Z chambers provides OPAL with the ability to perform high resolution measurements of the polar angle of tracks traversing the central detector. The Monte Carlo study of the single muon tracks performed by Routenburg[34] described in Section 2.2.2 also examined the θ resolutions of single muon tracks in the OPAL central detector with and without the vertex stereo cell high resolution z measurements. A plot of these is presented in Figure 2.6.

A good measurement of θ is useful for obtaining a high resolution mass measurement of weakly decaying particles such as the K_s^0 , Λ^0 particles and charmed mesons when they decay to two charged hadrons. This is because the mass resolution depends on the three dimensional momentum and opening angle of the decay particles. Ultimately a good mass resolution results in an improvement in the identification of the parents and the correct assignment of their decay products. Clean identification of these particles permit an examination of a variety of physics topics ranging from the measurement of branching ratios to studies of quark fragmentation functions. In addition, the ability to identify the charged decay products with their parent will contribute to a background reduction of any study that uses protons and pions.

A Monte Carlo study using GOPAL116 has been undertaken to study the effects of the vertex stereo cell on the mass resolutions of $K_s^0 \rightarrow \pi^+ \pi^-$ and $\Lambda^0 \rightarrow p \pi^-$.⁹ A single K_s^0 was generated isotropically with a momentum distribution produced from a parameterization of the LUND distributions compiled in '38. The K_s^0 was

⁹The branching ratio for these decays is 69% and 64% respectively.

Figure 2.5: OPAL Central Detector momentum resolution of a single muon track as a function of momentum using the GEANT based Monte Carlo Simulation of OPAL GOPAL114. (a) Vertex Detector Resolution = $70\mu\text{m}$ (b) Vertex Detector Resolution = 1 cm. This figure is from Reference [34].

Figure 2.6: OPAL Central Detector θ resolution of a single muon track as a function of momentum using the GEANT based Monte Carlo Simulation of OPAL GOPAL114. (a) Vertex Detector Resolution = $70\mu\text{m}$ (b) Vertex Detector Resolution = 1 cm. This figure is from Reference [34].

Detector	r- ϕ (cm)	z (cm)
Axial VXD	0.0040	3.00
Stereo VXD	0.5000	0.12
Jet	0.0130	6.00
Zed	0.5000	0.03

Table 2.3: Detector resolutions used in the gaussian smearing of the K^0 and Λ^0 mass resolution Monte Carlo studies.

decayed with the correct lifetime and its charged decay products tracked through the OPAL central detector with the appropriate interactions with the detector material handled by GEANT3[11]. The hits in each detector were gaussian smeared using the sigmas listed in Table 2.3. The smeared hits on each track were then fit with a circle. The transverse momentum was calculated from the curvature of the fitted track assuming a uniform magnetic field of 0.4 Tesla and the track θ was obtained using from a linear fit in s-z where s is the arc length in the (x,y) plane. From this information the momentum of each particle was calculated and, assuming that the daughters were properly identified as pions, the invariant mass of the $\pi^+\pi^-$ system was computed. The same procedure was used to study the $\Lambda^0 \rightarrow p\pi^-$ decay.

To explicitly examine the influence of the vertex stereo chamber on the K^0 mass measurement a second simulation was run which was identical to that described above but with the stereo z resolution set at 10 cm instead of 0.12 cm. The distributions for the case when both decay particles traversed both the vertex stereo and Z chambers are presented in Figures 2.7. The histograms displayed with solid lines represent the results of the calculations when a stereo z resolution of 0.12 mm was assumed. Overlaid on these distributions are those for which the stereo z resolution was assumed to be 10 cm (displayed using ' '). The mass resolutions are summarized in Table 2.4.

These studies demonstrate that a resolution of 0.12 cm in z at the vertex stereo

Figure 2.6: Monte Carlo simulation of the invariant mass of the (a,b) $\pi^+\pi^-$ system from K_S^0 decay (c,d) $p\pi^-$ system from Λ^0 decay.

	K_s^0		Λ^0	
stereo z σ (cm)	0.12	10.0	0.12	10.0
LUND Momentum Distribution	9.9	11.5	3.6	4.0
Uniform momentum between 5 and 10 GeV/c	8.6	12.1	3.3	3.7

Table 2.4: Summary of Monte Carlo calculation of the K_s^0 and Λ mass resolutions in MeV for large and small stereo z resolutions. Gaussian σ values are given when both stereo and Z chambers have hits on the tracks.

cell¹⁰ coupled with a measurement from the OPAL Z chambers improves the mass resolutions of the K_s^0 and Λ by 16%. It is evident from these results that in the case of the K_s^0 and Λ the resolution degradation is not entirely associated with the measurement of the decay opening angle. The momentum distributions of the K_s^0 and Λ have a median value of 2.9 and 3.9 GeV/c respectively. Below 5 GeV the momentum resolution is degraded by multiple Coulomb scattering as is evident in Figure 2.5. There are, however, interesting processes such as charmed hadron decay that are associated with the higher momenta K_s^0 s and Λ s. To investigate the influence of the stereo measurement on these higher momenta the Monte Carlo calculations were performed using a uniform distribution momenta between 5 and 10 GeV for stereo z resolution equal to 0.12 cm and 10.0 cm. The results of these calculations are included in Figure 2.7 and summarized Table 2.4. For momenta between 5 and 10 GeV the stereo z measurement improves the Λ^0 mass resolution by 12% while for the higher Q-value K_s^0 decay the mass resolution improves by 40%.

2.5 The Fast Z Vertex Measurement and the OPAL Trigger

The z coordinate associated with each drift time measurement in the vertex detector is measured using the difference in the arrival time of pulses at opposite ends of

¹⁰The mass resolutions were not sensitive to the exact value of the stereo z resolution. Values of the resolution as low as 0.05 cm were studied and were shown to have no significant effect on the results.

the wire. This 'fast z measurement', which has a resolution of several centimetres, provides information that is extremely useful for pattern recognition¹¹. In addition, because of the significant electrostatic deflections of the anode wires (a property dealt with extensively in Chapters 3 and 4), the fast z measurement is used in the initial time-to-distance conversion of the r - ϕ coordinate measurement.

The third function that these measurements perform is to improve the ability of the OPAL trigger to veto non-annihilation events. The e^+e^- annihilation events are expected at a rate of approximately 0.2 Hz. The background processes include cosmic rays (which are easily identified) with a rate of ~ 35 -100 Hz, and beam correlated events. The beam correlated processes consist of synchrotron radiation and interactions between electrons from the beam and the beam pipe or residual gas inside the accelerator vacuum pipe. Beam correlated background is a serious problem because of the dead time introduced in reading out these uninteresting events. A readout rate of 20 Hz (100 times the annihilation rate), for example, translates into a 10% dead time for OPAL[39]. To maintain a reasonable dead time it is important to filter the background at the hardware trigger level.

The synchrotron background is reduced by ensuring that no direct synchrotron radiation illuminates the beam pipe. This is accomplished by designing the collimators and beam pipe diameter (156 mm ID) to permit only those photons that have scattered at least once to hit the beam pipe. As a consequence, the synchrotron photons have energies below 200 keV and an expected rate of 10^6 photons/second. These will not affect the OPAL trigger.

The dominant beam correlated background originates from the interaction between off-momentum electrons and the beam pipe. These reduced energy beam particles are produced through beam-gas bremsstrahlung in the accelerator. The estimates of the rate for particles from either beam hitting the beam pipe within a

¹¹In this context pattern recognition refers to the correct association of individual hits in the chamber with the tracks that traversed the chamber.

region of $\pm 3.5m$ of the interaction point range as high as 1500 Hz[40].

One method of reducing beam-gas and beam-beam pipe background uses the fact that most of these events will have a primary vertex that is significantly displaced from $z=0$. A track trigger scheme has been incorporated into the OPAL trigger that looks for and rejects such vertex offsets by making use of the charge division z measurements available in the OPAL jet chamber and the time difference z measurements in the vertex detector[41]. These coarse but fast z measurements are used because the hardware trigger must make a decision to continue the readout of an event within $16\mu s$ in order to provide sufficient time to reset the detector before the next bunch crossing (which occurs every $22\mu s$). The scheme that has been adopted is based on the fact that all central detector hits on a track originating from a primary vertex at $z=0$ will have the same value of z/r . Using a RAM lookup table, the fast z measurements are converted into z/r values.

Values of z/r are histogrammed in four 2×2 histograms, one for the vertex detector and three for different radial segments of the jet chamber. Each histogram is divided into 24ϕ by $32 z/r$ bins. A jet chamber ϕ bin is filled from two adjacent jet sectors while each vertex ϕ bin is filled from three adjacent vertex sectors. This accounts for tracks that cross boundaries in the jet chamber. A track is identified by peaks in the same ϕ and z/r bin (within some tolerance) of different histograms. The number of the four histograms that must have peaks in the same bin is θ dependent with the minimum being two. An event passes the track trigger if there is at least one such track.

The z/r acceptance for the inner jet radial segment and vertex detector is ± 3.6 . This enables the trigger to handle tracks with a θ as low as 16° . With this acceptance the vertex z/r bin width is roughly 0.23. If the single hit z/r resolution is to be equal to this bin width, the vertex time-difference z measurement should have a resolution of approximately $3 cm$.

A Monte Carlo simulation of this track trigger scheme has been performed [41]. The influence of the vertex detector on the trigger is evident in Figure 2.8 which is taken from Reference [41]. This is a plot of the percentage of events that are rejected by the track trigger as a function of the z position of the interaction between the off-momentum beam particles and beam pipe, for three tolerances on the agreement between the vertex and jet chamber z/r match: ± 1 bin, ± 3 bin and with no vertex detector requirement. Without the vertex detector, only a 50% rejection rate can be achieved for a vertex located as far out as $z = \pm 35$ cm.

The tolerance on the agreement between the bins in the jet and vertex detector will be adjusted to ensure that a small sample of identifiable background events will be accepted as a means of studying this background in the $z=0$ region [41]. As a consequence, it is clear that the vertex time difference z resolution need not be as good as 3 cm, but such a resolution would provide greater flexibility in setting up the track trigger. In Reference [41] it is suggested that the number of z/r bins between the vertex peak and jet chamber peaks in the track trigger histogram be less than ± 3 bins. Included in Figure 2.8 is the rejection efficiency using the track trigger as a function of the vertex position in z , z_0 , for a tolerance of ± 3 bins. This corresponds to a 50% rejection rate occurring at $z = \pm 15$ cm and nearly 100% at $z = \pm 30$ cm.

In the most pessimistic scenario 1500 off-momentum beam particles hit the beam pipe within ± 3.5 m of the interaction point each second. The angular distribution of the incident particles was not thoroughly modelled but it was assumed in Reference [40] that the angle of incidence would be small and therefore only a subset of the 1500 would actually provide potential background. If it assumed that these 1500 beam pipe interactions are uniformly distributed in z and a ± 3 z/r bin tolerance on the vertex-jet match is used in the track trigger then the background from such events is reduced by 90% by the track trigger. So if, for example, as many

as 20% of 1500 beam pipe interactions per second generate particles that enter the acceptance of the track trigger, then the background rate would be 30 Hz which corresponds to a dead time of 15%.

In the study in Reference [41] one vertex z/r bin in the track trigger corresponded to 3 cm in z . Therefore a tolerance of ± 3 z/r bins in the track trigger corresponds to an equivalent vertex z RMS of $(2 \cdot 3 \text{ bins} \cdot 3 \text{ cm})/\sqrt{12}$ or 5 cm . From this and Figure 2.8 the dead time can be estimated as a function of the vertex time difference z resolution, σ_{ztd} , and the proportion of the 1500 Hz beam pipe interaction rate that produces background tracks in the detector, f_{bkgnd} , assuming that the tolerance on the vertex-jet match in the trigger is ± 1 bin:

$$\% \text{dead time} \sim 15 \cdot f_{bkgnd} \cdot \sigma_{ztd} (cm)$$

Figure 2.8: OPAL Track Trigger: Variation of the fraction of events rejected by the trigger with vertex position z_0 . The vertex detector time-difference z resolution was assumed to be 3 cm. This figure is from Reference [41].

Chapter 3

Vertex Detector Design and the Prototype

It has been demonstrated that a vertex detector at LEP will be of considerable use for the study of a wide range of Standard Model physics. The OPAL vertex detector is separated radially into an axial region and a stereo region each containing thirty-six 10° jet cells as shown in the schematic diagram of Figure 3.1. The high resolution r - ϕ measurement is performed in the axial cells each of which has twelve anode sense wires placed 5.3 mm apart. The inner and outer anodes are located at radii of 103 mm and 161 mm respectively. The high precision z measurement of the vertex detector is obtained by introducing a stereo angle of approximately 4° for the stereo cell wires. Each stereo cell has six anodes spaced by 5.0 mm with the innermost wire at a radius of 188 mm and the outermost at 213 mm . The maximum drift distance ranges from 9 to 14 mm in the axial cells and from 16 to 19 mm in the stereo cells. The vertex detector must be able to operate with either a 'hot' or a 'cool' gas in the pressure range of 3 to 4 bar . The fast timing requirements in the 'hot' gas operation precludes the use of flash ADCs (FADC) thus necessitating the use of fast discriminators coupled to a multihit readout.

A full scale prototype of the vertex detector was constructed to investigate design and construction issues and to gain operational experience. The prototype had four

Figure 3.1: Schematic diagram of the OPAL vertex detector

axial cells and two stereo cells for a total of sixty sense wires. The electronics had approached the final design stage and the prototype tests provided the opportunity for their detailed fine tuning. In addition the tests provided the opportunity to investigate various chamber gases and the electrostatic properties of the chamber. The prototype results motivated some design modifications for the final chamber. Experiments were performed with the prototype using a test beam. In these tests it was operated with with argon-ethane (50% - 50%) up to 3.75 bar and CO₂-isobutane (80% - 20%) up to 2.50 bar.

3.1 Justification for the Design

As previously stated, OPAL's general philosophy has been to provide a reliable detector that will be ready at LEP turn-on. A consequence of this is that new technologies that have never been used within the constraints of an e^+e^- collider environment were not seriously considered for initial OPAL operation. From the point of view of vertex detection this meant that the design effort was directed

towards the development of a high resolution drift chamber. The only competing technology would have been a solid state device (silicon strips or CCDs). However, because of the large size of the initial LEP beam pipe and its relation to multiple scattering as outlined in Chapter 2 there is little to be gained in the impact parameter measurements when such devices are used during the initial operation of LEP[42]. The disadvantage of using that technology lies in the fact that it would be unlikely to have such a device operational in time for the startup of LEP¹.

The physical dimensions of the detector are dictated by the available space within the rest of the OPAL experiment. At OPAL the vertex detector occupies the region between the beam pipe and the jet chamber. This imposes an inner radius of 85 mm on the vertex detector and an outer radius of 235 mm. The length of the vertex chamber is constrained by anode wire electrostatic stability, the presence of jet chamber laser calibration equipment and the requirement that the forward detector not be shadowed by any material.² These set the active length of detector at 1000 mm.

The detector is to provide tracking with a spatial resolution of around 50 μm in r - ϕ for use in the measurement of vertex topologies. The jet cell geometry was chosen to provide this high resolution measurement. The jet cell is the cylindrical equivalent to the classic multiwire planar drift cells where instead of planes the cylindrical volume is subdivided into wedges in ϕ . The jet design was first used by JADE 43 at PETRA and was proven to be a success. This traditional jet design was chosen for the OPAL vertex detector because the electrostatics are reliably calculated with a minimum of boundary effects. A consequence of the well defined electrostatic field is that the time-to-distance relationships are relatively simple even if a gas with a non-saturated drift velocity is used. Moreover, there is reasonable multihit

¹This statement is supported by the experience of the DELPHI and ALEPH experiments at LEP. Both of these experiments have planned to have solid state vertex detectors but it is unlikely that either will have the device ready when LEP turns on.

²This implies that no material be placed within a 120 milliradian cone around the beam pipe.

capability and the response of the detector is nearly independent of the particle direction. More complex jet chamber designs exist, such as the time expansion jet chamber [44], but the classic jet design is easier to implement.

Each plane of sense wires is associated with the two drift regions on either side. Since only a drift time is measured the hit space point may be on either side of the anode plane. This necessitates the use of some mechanism for distinguishing from which side of the plane the drifting electrons originated. The resolution of this 'left-right' ambiguity is accomplished in the OPAL vertex detector by introducing a stagger to the anode sense wires: alternate wires are offset into opposite drift regions as can be seen in Figure 3.2. This figure is a display of a particle track traversing the prototype detector. Hits from both left and right side hypotheses are shown in the display. The stagger of the anode wires introduces a stagger in the hits of the wrong side hypothesis and in this way resolves the left-right ambiguity.

The measurement of the difference in the arrival time of the pulses produced by a single ionization event arriving at opposite ends of a sense wire provides a coarse vertex z measurement for each hit with a resolution of several centimetres. As discussed in Chapter 2, this measurement will be used in the OPAL trigger and for initial pattern recognition in the vertex detector track reconstruction program. The use of the hit-by-hit z information assists in the correct assignment of hits to tracks within the vertex detector that overlap in r - ϕ but are well separated in r - z . In addition, there are significant electrostatic forces on the wires causing them to deflect into parabolic shapes. These produce a z -dependent position of the wires and the coarse z measurement is useful in providing initial information on the wire position in the r - ϕ plane for each hit.

The high resolution z measurements are provided by the stereo wires. These provide measurements that are useful for calculating three dimensional momenta. They also provide a means of calibrating the time difference z measurement and

Figure 3.2: Display of a particle traversing the OPAL prototype detector. Clearly seen is the anode wire stagger that is used to resolve the 'left-right' ambiguity. Both left and right side hypotheses of the hits are shown in the display. The correct hypothesis hits are joined by lines.

increase the precision of the z-dependent wire position in the r - ϕ plane of the axial cell.

3.2 Drift Chamber Gases

The vertex detector will be contained in the same pressure vessel as the Jet and Zed chambers but it will possess a separate gas volume. This allows the chamber to operate with a gas that is optimized for high spatial resolution and reliability within the constraints of an e^+e^- experiment. The OPAL central detector pressure vessel is rated for operation up to 4 bar. Therefore operation beyond this pressure was not considered for the experiments with the prototype.

There are a variety of properties of a gas that influence its operation in a high resolution drift chamber. These include its primary ionization and thermalization characteristics, velocity-electric field dependency, electron diffusion, the Lorentz angle (when the chamber is operated in a magnetic field), gain characteristics, and radiation hardness. The influence of each of these is discussed in some detail in Appendix B. From these various properties two generic classes of drift chamber gas have been identified: 'hot' and 'cool'. Cool gases have drift velocities that are roughly proportional to the electric field and diffusion that approaches the thermal limit. Hot gases have drift velocities that increase rapidly and saturate at low electric fields and diffusion that is several times that of the thermal limit. Because the Lorentz angle usually increases with drift velocity, cool gases have significantly lower Lorentz angles than hot gases under equivalent field conditions.

Usually a hot gas has a large proportion of argon while the cool gases avoid it altogether. This is because the hot gas properties are associated with the presence of the Ramsauer-Townsend effect³ which occurs in argon based gases. An additional consequence of the presence of argon is that hot gases usually have higher gain than

³This is described in Appendix B.

cool gases. This enables a drift chamber to be operated with lower voltages when a hot gas is used compared to operation at the same gain and pressure as when a cool gas is used. The design of a particular drift chamber will allow certain maximum voltages for producing the drift and anode gain electric fields. Operation at higher gas pressures requires higher voltages operation but improves the primary ionization and diffusion properties.

The experiments with the prototype have focused on studying the detector response when operated with a gas from each category. The broad velocity saturation properties of argon-ethane (50% – 50%), as seen in Figure 3.3, makes this a very attractive and popular hot gas. The gain characteristics of this gas are such that the prototype was able to operate up to 3.75 bar. The operating drift velocity was approximately $50 \mu\text{m}/\text{ns}$, so to attain the design spatial resolution of $50 \mu\text{m}$ a timing resolution of roughly 1 ns was required. The timing measurement is made more difficult by fluctuations in electron cluster sizes (described in Appendix B) which tends to be more severe in argon. It is clear from diffusion characteristics of argon-ethane, as presented in Figure 3.3 that it also potentially provides a significant contribution to resolution degradation. The cool gas examined in these studies was CO_2 -isobutane (80% – 20%). The velocity and diffusion characteristics are presented in Figure 3.4. Elimination of the argon ensured that cluster size fluctuations and diffusion was minimal. Unfortunately, the gas gain is significantly lower than in the hot gas and, coupled with the electrostatic properties of the prototype, this limited the operating pressure to 2.5 bar and the velocity to between 10 and $15 \mu\text{m}/\text{ns}$.

3.3 Mechanical and Electrostatic Design

The mechanical design and construction of both the prototype and final chambers were carried out at Carleton University and NRC. A schematic diagram showing some mechanical features of the prototype is presented in Figure 3.5. In the vertex

Figure 3.3: (a) Diffusion coefficient and (b) Velocity as a function of Electric Field in Argon-Ethane (50-50). From Reference [45].

Figure 3.4: Velocity and Diffusion vs Electric Field in CO_2 -isobutane (80-20). From Reference[46].

Figure 3.5: Schematic picture of the OPAL vertex prototype

detector prototype the wires were strung between two 25 mm thick G10⁴ end plates which were held apart by four aluminum rods. The preamplifiers and high voltage printed circuit distribution cards were mounted on each end plate in a region enclosed by an aluminum cylinder that extended in z from 500 mm to 795 mm. A 1 mm thick carbon fibre tube enclosed the prototype at the outer radius. In the final detector such a tube is used to hold apart the end plates. The carbon fibre tube was coated with a conducting paint to provide end-to-end grounding which was necessary for low noise operation of the preamplifiers. The carbon fibre tube was also used to define the gas volume at the outer radius. The inner radius of the gas volume was defined by an aluminized mylar window and the volume was closed off at each end by the aluminum cylinder and a gas bulkhead.

A classic jet cell geometry with radial anode and cathode planes was used in the chamber design. The wire pattern of the prototype chamber is shown in a cross sectional diagram in Figure 3.6. The left-right tracking ambiguity was resolved in the prototype by introducing a $\pm 150 \mu\text{m}$ stagger to the anode wires. The anodes were $20 \mu\text{m}$ diameter gold plated tungsten-rhenium wires strung under 50 g-wt tension. A set of $100 \mu\text{m}$ diameter gold plated copper-beryllium guard wires was located between the anode wires. These wires determined the sampling width and electrostatic focusing characteristics of the cell and provided some control of the anode surface field. The cathode planes were composed of $100 \mu\text{m}$ diameter copper-beryllium wires placed 1 mm apart. The anode, guard and cathode wire locations were defined by plexiglass combs which were positioned on the G10 end plates using two glass dowels. In the axial cells an anode and cathode plane were cut on opposite sides of the same comb. A picture of the type of comb used in the axial section of final vertex detector is shown in Figure 3.7. The wires were soldered and epoxied onto printed circuit board assemblies that were fastened to the end plates. The anode comb grooves relative to comb dowels were cut to a precision of $\pm 10 \mu\text{m}$ in

⁴G10 is a fibreglass composite material typically consisting of 60% SiO_2 and 40% epoxy.

Figure 3.6: Wire pattern in the OPAL vertex prototype.

Figure 3.7: An anode, guard and cathode wire positioning comb of the type used in the final detector.

the prototype. The radial boundaries of the cells were defined by rings of $100\ \mu\text{m}$ diameter copper-beryllium field shaping wires. They were located and crimped using feedthroughs in the G10 end plates. All of the $100\ \mu\text{m}$ wires in the prototype were strung under 300 g-wt tension.

3.4 Electrostatics and High Voltage

The electrostatic operating conditions of the chamber were defined by two independent electric fields: the anode surface field, which determined the gas gain, and the drift field, which defines a uniform field extending from approximately $3\ \text{mm}$ from the anode plane to the cathode. The anodes were operated at DC ground while the cathodes and guards were operated at negative high voltage. The drift field was perpendicular to the anode-guard plane as shown in Figure 3.8. This necessitated the use of a resistor divider network in the cathode plane which was instrumented using $1\ \text{M}\Omega$ surface mount resistors between pairs of adjacent cathode wires. Fig-

Figure 3.8: Cross section of an axial cell in the prototype showing drift paths

Drift Field (kV/cm)	Anode Surface Field (kV/cm)	Highest Cathode Voltage (kV)	Central Guard Voltage (kV)
1.8	360	4.277	2.044
1.8	400	4.484	2.390
2.4	400	5.292	2.034
2.4	435	5.472	2.340
2.8	435	6.026	2.100
2.8	455	6.120	2.270
3.0	455	6.390	2.150
3.0	475	6.485	2.325
3.0	496	6.585	2.500
3.0	520	6.720	2.740
3.2	500	6.895	2.440
3.2	520	6.990	2.610
3.2	540	7.085	2.780
3.2	560	7.180	2.950
3.2	600	7.370	3.290

Table 3.1: High voltage settings used in the OPAL vertex prototype axial cells. The voltages on the central guard wires and the highest cathode voltages are given for several drift and anode surface field configurations.

Figure 3.9 shows the system of high voltage supplies that was used in the prototype. A list of the guard wire voltages and highest cathode voltages that were used in the prototype detector along with the corresponding drift and anode surface fields is presented in Table 3.1.

The radial boundaries of the electrostatic cell were defined by a pair of field shaping rings at the inner radius and another pair at the outer radius. The potential of each field shaping wire was set by a divider network designed to reduce any electric field asymmetry between edge and central anodes. Edge guard wires were set to different potentials from those in the middle to maintain a uniform gain on all anode wires.

All potentials in the chamber were constrained by the requirement that no cathode-like surface field exceed 20 kV/cm . Because of this it was necessary to

Figure 3.9: High voltage supply network used in the prototype. (a) Guard system (b) Field ring wires, cathodes and foils

increase the number of field wires at both ends of the cathodes. In this region the resistor divider chains were tuned to minimize the surface fields while trying to maintain as uniform a drift field as possible. The maximum drift field used in the prototype was 3.2 kV/cm and the maximum anode surface field was 600 kV/cm . At the maximum drift field the electrostatic bow of the anode wires was $300 \mu\text{m}$ at the centre of the chamber ($z=0$).

The axial and stereo sectors were electrostatically isolated from each other by a pair of foils mounted on either side of a mylar sheet placed at a radius of 177 mm . Foils were also located at the inner radius of the detector, adjacent the inner gas window, and at the outer radius, mounted on the inside of the carbon fibre tube. These foils were charged to a potential of between 3 and 4 kV and served to close off the cell fields.

The high voltage was supplied to the guard wires, foils and anode plane ends of the field ring chains ('field ring low') using Lecroy HV4032A supplies as shown in Figure 3.10. The 'field ring low' voltages were supplied with 3 kV Lecroy 'pods' (HV4032A3N) while the guards and foils were supplied with 7 kV Lecroy 'pods' (HV4032A7N). Voltages were entered from the data acquisition computer (DIGITAL LSI model BA11-SF) using the RT11-MULTI software interface and regulated by the on-board microprocessor. The voltages are regulated at the $\pm(0.1\% + 1.5 \text{ V})$ level for the 3 kV 'pods' and $\pm(0.1\% + 3 \text{ V})$ for the 7 kV 'pods'. No external monitoring was performed. Bertan 380N 10 kV supplies were used to supply the cathodes and wires at the cathode plane end of the field shaping rings ('field ring high'). Although rated for drifts of $\pm 0.02\%$ over eight hours, these supplies did not have an intelligent on-board monitor. To compensate for this, the monitor voltages were sampled using a Lecroy LG8252 scanning ADC and written into the event buffer for off-line monitoring at each accepted trigger. The sampling period was 2 ms and the conversion time was $60 \mu\text{s}$ for these measurements.

Figure 3.10: High voltage control system used in the experiments with the prototype.

Before entering the pressure vessel all the high voltage lines passed through filter networks to minimize high frequency voltage fluctuations and parasitic noise that could pass through to the signals. The guard wire filters are shown in Figure 3.9. For the cathode and field supplies the resistors in the filters were $10\text{ k}\Omega$ instead of the $10\text{ M}\Omega$ used in the guard circuit. Noise was further reduced by ensuring that the high voltage and readout systems shared a common RF earth.

3.5 Readout Electronics

The readout system for the OPAL vertex detector was designed and constructed at the Rutherford Appleton Laboratory in the United Kingdom. Both ends of each anode wire were instrumented with single ended preamplifiers whose output signals were transmitted down 38 metres of coaxial cable to a 'Converter Module'. These modules digitized the time and amplitude of the signals and passed them to a CAMAC dataway. A block diagram of the readout system of a single wire is

Figure 3.11: Block Diagram of OPAL Vertex Detector Readout System

presented in Figure 3.11.

Each end of an anode wire was terminated in its characteristic impedance of $360\ \Omega$ with a low noise preamplifier which had a gain of three and a bandwidth of 100 MHz . One preamplifier card serviced a group of twelve (axial sector) or six (stereo sector) anodes and was mounted directly on the end of the chamber. The guard wires were terminated with an impedance of $100\ \Omega$ onto the ground plane of the preamplifier cards.

As discussed in Chapter 2 a measurable signal is generated on an anode wire by the movement of the positive ions away from the wire. At the same time a pulse of opposite polarity is produced on all nearby electrodes. Although the presence

Figure 3.12: Schematic of induced crosstalk effects in a drift chamber.

of the guard wires minimizes the amount of this induced signal on neighbouring sense wires, there is still a significant amount of this crosstalk between adjacent sense wires. In a jet chamber the problem of crosstalk is important because the arrival time of the electrons is highly correlated for all wires within a given sector. Figure 3.12 shows how the induced crosstalk can interfere with a drift time measurement. In an attempt to minimize these effects the preamplifiers were fitted with crosstalk compensating resistors which fed 7% of the signal to the adjacent channels and 2% to the next adjacent channels.

The preamplifiers also had a pole-zero circuit which is used to improve the two hit resolution. If more than one particle traverses the same jet cell, as will be the case with almost all hadronic events at LEP, then an independent drift time should be measured for each particle. The particle that passes nearest an anode wire generates a pulse with an undistorted leading edge. Unfortunately, the pulse's long tail can distort a later pulse that is associated with a different particle. If the pulses are too close in time then the superposition of the two pulses may keep the pulse amplitude above the discrimination level and prevent the discriminator from retriggering on

the second pulse. To minimize the inefficiency of the detection of later arriving pulses caused by this effect the pulses are differentiated in the preamplifier. The differentiator has 'pole-zero cancellation' which ensures that there is no undershoot of the differentiated pulse.

Each Converter Module services two sense wires and is mounted in a triple height Eurocard crate. The input to each channel is amplified to a level suitable for the discrimination and analogue summing circuits. The analogue output pulses from both ends of a wire are summed and then fed to a FADC to provide a low resolution measure of pulse amplitude. The separate signals from each end of an anode wire are also fed to independent constant fraction discrimination circuits after a being amplified by a factor of 40. The discrimination circuit included a noise rejection threshold and could be modified to operate as dual threshold leading-edge discriminators as well. The two discriminator signals, one of which is delayed as a means of maintaining the 'wire end' sense, provide the input to both meantimer and time-difference digitizers. External monitoring for each wire end was available from a $3\frac{1}{4}$ gain, $50\ \Omega$ impedance analogue output.

The drift time time-to-digital (TDC) 'start' was provided by a beam scintillator signal while the 'stop' came from the output of the meantimer. Using the mean time of the signals from opposite ends of the sense wire reduces the error in the drift time measurement associated with the z-dependent propagation delay along the wire. A crystal-referenced 100 MHz gated oscillator clocks a synchronous counter to provide eight low resolution bits of the drift time measurement. Four additional high resolution bits are provided by a circuit that interpolates between clock pulses. The interpolation is performed by starting a ramp with the output of the meantimer and measuring the height of the ramp at the next clock pulse with a four bit FADC. The resultant twelve bit TDC has a resolution of 0.625 ns and a range of $2.56\ \mu\text{s}$.

The end-to-end time difference is measured using an integration type time-to-

amplitude converter (TAC) followed by a six bit FADC. The reference inputs of the FADC are controlled by an 'autocalibration' operation performed between data acquisition periods. Test pulses are injected into the preamplifier at one end of the sense wire and then at the other. The FADC reference inputs are automatically adjusted until the TDC output reads zero for one end and full scale for the other. With typical anode signal propagation times, the time-difference TDC has a resolution of approximately 100 ps which, in the vertex detector, is equivalent to 2 cm.

A timeout circuit of the time-difference TDC is used in the memory control logic which ensures that only digitizations from pairs of pulses originating from the same hit are stored. Up to fifteen conversions per wire can be stored in the ECL memory during each data acquisition period and the total conversion time for each hit is less than 25 ns. The data for each hit consist of 12 bits for drift time, 6 bits for time-difference, 5 bits for signal amplitude, 4 bits for hit count/wire/machine cycle and 5 bits for module address. These data are transmitted as two 16 bit words over a standard CAMAC highway.

In addition to the readout of the Converter Modules, information from a number of monitors was also recorded. The pressure of the gas was monitored using a Schae-vitz pressure transducer model P713-0025. This had a sensitivity of 1.143 V/bar and an absolute precision of better than 5 mbar. The ambient temperature was monitored using an Analog Devices temperature sensor model AD590. The device was operated in a calibrated two temperature trim mode that provided a sensitivity of 100 mV/°C. Components in the two temperature trim circuit had temperature coefficients of 200 ppm/°C and the temperature drifted over less than $\pm 10^\circ\text{C}$ from ambient during the tests. Based on this and a crude estimate of the temperature gradient between the probe and the gas (less than 0.5°C) an absolute precision of $\pm 1^\circ\text{C}$ is estimated for the measurement of the temperature of the gas. Finally, six of the chamber wires were instrumented at both ends with a 12 bit Lecroy 2249W

integrating ADC. These provided a high resolution measurement of the total charge of a pulse for monitoring gain and other systematics associated with charge.

3.6 Intrinsic Limitations of Drift Distance Measurements

The objective of the experiments with the prototype was to quantitatively evaluate the response of the detector when it was operated with a hot and a cool gas. As part of this evaluation the expected intrinsic resolution of the drift distance measurement was investigated using a Monte Carlo simulation of the detector. Published values of the drift velocity-electric field dependence, diffusion characteristics, gas gain and electron clustering characteristics provided the input to the simulations. The simulations examined the resolution as a function of drift distance for both argon-ethane(50-50) and CO₂-isobutane(80-20). Details of the experimental evaluation of the intrinsic resolutions are presented in Chapter 4.

The intrinsic spatial resolution of the high precision drift measurement is limited by statistical fluctuations associated with the following effects.

1. *The physical extension and statistical spread of the initial ionization:* The extension is dominated by δ -ray production which can be identified by the anomalously large amount of deposited charge and the large deviation of such a hit from a track. The statistical spread is not a dominant limitation if the isochrones associated with the charge contributing to the signal are uniform. In a jet chamber this is only a problem for tracks passing near an anode wire provided the angle of the track relative to the anode plane is small and the timing measurement is associated with the arrival of the first few clusters of electrons.
2. *The longitudinal diffusion of the drifting electrons:* This varies as the

square root of the drift distance and is a function of the gas, pressure (P), and the drift field (E). If E/P is kept constant, the diffusion is inversely proportional to the square root of the pressure. The effects of diffusion can be reduced by minimizing the drift distance, operating at high pressure and maximizing the number of electrons that can contribute to the timing by making the isochrones as uniform as possible.

3. *The resolution of the electronics:* The timing can be degraded by noise and TDC sampling limitations and fluctuations in the pulse shape. The lack of uniformity of pulse shapes is associated with fluctuations in the numbers of electrons in the primary ionization clusters and to a lesser extent by fluctuations in the number of electrons produced in the avalanche. These effects may be minimized by timing off the part of the signal associated with the first electrons that arrive at the anode. This requires a very high signal-to-noise ratio which may be obtained by operating the chamber with high gains. An alternative solution is to operate in the limited streamer mode (gains of 10^7) which yields pulse uniformity. Operation with high gain generates a large amount of space charge and is not feasible in a multihit jet cell design. Moreover, the chamber lifetime is lengthened by operating at lower gain. The amount of the cluster size fluctuations is gas dependent with argon generally having larger cluster fluctuations than polyatomic gases. Reduction in the proportion of argon may reduce the impact of this effect. The overall loss of the timing resolution can be made less significant by reducing the sensitivity of the spatial measurement to the timing measurement by operating with a cool gas.

A useful method for studying whether or not these effects account for the observed intrinsic resolution of the detector is to use a Monte Carlo simulation of

the detection process [47]. The program described in Reference [47] can model ionization and clustering, detailed electron transport and gas gain fluctuations. Of particular interest are physical processes that are, at most, weakly dependent on the details of the electric field⁵. Therefore the detailed treatment of electron transport was replaced with an electron transport treatment based on a simple model of the electrostatics which is described below. 100 tracks were generated at the same position in the simulated drift space of a sense wire and a gaussian fit performed to the distribution of electron arrival times as determined by a simulation of the constant fraction discriminator. The standard deviation of this distribution was used as the theoretical intrinsic timing resolution. To convert this to a spatial resolution the timing resolution was multiplied by the value of the velocity at the original position of the ionization.

In the simulation primary electrons were distributed randomly along a track that passed through the drift cell. The number of primary electrons depends on the gas and is proportional to the gas pressure. For the argon-ethane(50-50) simulation 30 electrons/(cm · bar) was used while in CO₂-isobutane 36 electrons/(cm · bar) was used. The number of electrons in a cluster originating at the position of each of the primary electrons was determined using the distribution of cluster sizes in pure argon described in Reference [48]. Each electron was then drifted to the wire using a simplified model of the electric field in the detector.

In this simple model the space was divided into a uniform and a nonuniform field region:

$$\vec{E}(x, y) = \begin{cases} (A_1/r + A_2)\hat{r} & r \leq R \\ (A_1/R + A_2)\hat{x} & r > R \end{cases}$$

R in this expression represents the maximum isochrone radius which in this treatment is equivalent to the distance from the wire at which the equipotentials become straight lines that are parallel to the anode plane. This model provided a means of

⁵Included in this are cluster fluctuations, isochrone structure, diffusion, avalanche fluctuations, electronics response and noise.

generating an isochrone structure that was similar to the true isochrone structure of the detector for all electrons except those that contributed to the tail of the pulse.

In the study of the saturated gas, argon-ethane(50-50), a velocity of $53 \mu\text{m/ns}$ was used and was assumed to be independent of the field. For the CO_2 -isobutane(80-20) study the velocity depended linearly on E/P as $8.6 \cdot (E/P) \mu\text{m/ns}$.

The total distance travelled by an electron was smeared by a gaussian distribution that represented the contribution of diffusion. The time corresponding to the diffused distance was then entered in a histogram of 'electron arrival times' with the bin width set equal to one TDC clock count (0.625 ns). A gas gain of $3 \cdot 10^4$ was assumed for both gases and gas gain fluctuations were simulated for each electron by weighting each histogram entry by a factor x which was distributed as:

$$A(x) = \text{constant} \cdot x e^{-1.5x}.$$

This distribution describes fluctuations of avalanche sizes in argon as published in Reference [49].

The simulation of the development of the charge on the wire from positive ion motion was combined with a simulation of the sense wire termination by convoluting the electron arrival times with

$$\frac{\text{constant}}{1 + t/t_0}.$$

t_0 is defined in Appendix B.

The response function of the preamplifier's pole-zero network, the 40 m of coaxial cable and the Converter Board amplifier was measured and parameterized. This response function was then convoluted with the pulse. Noise was then added to the pulse.

The constant fraction discriminator was modelled by comparing the height of a copy of the pulse delayed by 7.5 ns to the height of a copy of the pulse attenuated

2

MicroD

Figure 3.13: Monte Carlo Simulation of Intrinsic Resolution in the OPAL Vertex Detector Prototype

by a factor of two. The point where these crossed was used as the simulated arrival time measurement.

The parameters in the simulation have been adjusted to correspond to the conditions used during the vertex prototype tests and are summarized in Table 3.2. The intrinsic resolution as a function of drift distance was calculated for each gas and the results are plotted in Figure 3.13.

In summary, this simulation indicates that in argon-ethane(50-50) a resolution of between 50 and $60 \mu m$ is expected for both 3.0 and 3.75 bar . There is little degradation of the resolution with drift distance indicating that diffusion does not

Gas	argon ethane (50-50)		CO ₂ -isobutane	
Pressure (bar)	3.00	3.75	2	2.5
E _d (kV/cm)	3.2	3.2	3.2	3.2
v _d (μm/ns)	53	53	$13.7 \cdot \frac{E[kV/cm]}{3.2}$	$11.0 \cdot \frac{E[kV/cm]}{3.2}$
σ _L (μm√ $\frac{bar}{cm}$)	170	170	70	70
E _a (kV/cm)	520	540	540	600
Gain	3×10^4	3×10^4	3×10^4	3×10^4

Table 3.2: OPAL Vertex Detector Prototype Beam Tests: Parameters Used in the Monte Carlo Simulation

dominate the resolution. The most likely hypothesis was that the timing resolution was dominated by fluctuations in the sizes of the electron cluster. The Monte Carlo simulation was used to examine whether or not this was a viable hypothesis by turning off the effects of cluster fluctuations. The resulting resolution calculations are included in Figure 3.13. These indicate that the cluster size fluctuations introduce nearly a factor of two degradation in the resolution. Experimental evidence that supports this is presented in the following chapter.

In CO₂-isobutane a resolution of between 20 and 30 μm is anticipated and the diffusion introduces some degradation with drift distance. The cluster fluctuations also degrade the timing resolution in this gas but the time-to-distance relation transforms the poor timing measurement into a good distance measurement.

Chapter 4

Performance of the Prototype: Test Beam Studies

The objective of the experiments with the prototype was to quantitatively evaluate the response of the detector when operated with a hot and a cool gas. The properties of the design that limit the spatial resolution were studied by measuring the intrinsic resolutions as a function of gas and gas pressure, drift field, drift distance, gas gain and track orientation and position.

Section 4.1 provides an overview of the setup used in the experiments with the prototype. Included is a description of the test beam facility, the data acquisition and analysis procedures, and an evaluation of the gas composition and high voltage stability. An evaluation of various aspects of the electronics is presented in Section 4.2.

Three resolution quantities were examined: the r - ϕ drift time intrinsic resolution, the time-difference z resolution and the multihit resolution. The intrinsic resolution of the drift time measurement is discussed in Section 4.3. Trends within this data suggested that the intrinsic resolution was degraded by crosstalk effects. This is pursued in Section 4.4. The ability of this detector to identify the presence of ionization from more than one particle traversing the drift space of the same sense wire is discussed in Section 4.6.

Further insight into the limitations of intrinsic resolution was gained by experimenting with time pick-off methods described in Section 4.5. These studies provided information that was used to optimize the time pick-off method but also confirmed the hypothesis that the intrinsic drift time resolution of the hot gas is dominated by pulse shape fluctuations while the time-difference measurements are limited mainly by noise.

The chapter concludes by examining the stereo z resolution and uses this information to obtain a measure of the absolute resolution of the detector.

4.1 Test Beam Setup

4.1.1 Test beam

The prototype was studied using a test beam of 30 and 45 GeV/c pions in the X5 beam line of the West Area at CERN. This tertiary particle test beam was originally derived from the slow extraction of 450 GeV/c protons from the CERN SPS accelerator. The extracted beam typically consisted of a few 10^{12} protons per SPS spill. This beam was directed onto a 175 mm long ($0.5 L_{RAD}$) beryllium target, T1, at the West Area Switch Yard. The secondary particles produced in this target were split into two beams, H1 and H3. The H3 beam contained particles having energies up to 350 GeV with the highest intensities (typically several 10^7 /burst) available when a secondary proton beam was selected. This was the operating mode during the prototype tests. H3 is split into three tertiary beams one of which is the X5 beam. The X5 beam was directed onto a 400 mm long beryllium target to produce the final beam of pions and electrons. A 10 mm long lead absorber, located down stream of the target, was used to reduce the number of electrons in the beam. The momenta used were 30 GeV and 45 GeV with an RMS momentum spread of $\pm 3.5\%$ and the divergence of the beam at the prototype was less than 0.5 $mrad$.

The X5 target received a burst every 14.4 s that lasted 2820 ms. A signal¹ preceding each burst by 5 ms was provided by the test beam facility for use in the hardware event selection or 'trigger' of the experiment. A second signal indicating the end of the burst (*EOB*) was also provided and was used to reset burst scalers.

The chamber was placed in a pressure vessel which was mounted on a platform movable in the z-direction and which also could be rotated through both polar (θ) and azimuthal (ϕ) angles. The beam transverse width was sufficient to illuminate two axial cells simultaneously. The hardware trigger consisted of a coincidence in a pair of crossed scintillators located up-stream of the chamber occurring within the -5ms and *EOB* signals. A beam event was accepted if, in addition to the hardware trigger, there was a hit in a delay line multiwire proportional chamber (MWPC) placed down stream of the chamber, three hits anywhere in the chamber itself and if there were no other hardware triggers within $\pm 2 \mu\text{s}$ of the event. Typically 400 particles triggered the crossed scintillation beam counters per burst. Of these, 150 were accepted by the prototype trigger. The multiple tracks for the two track resolution studies were produced by interactions in a 40 cm long paraffin target which was placed between the crossed scintillators and the chamber.

4.1.2 Data acquisition and analysis

A modified version of the data acquisition program *MULTI50* was run on a DIGITAL LSI model BA11-SF computer. It provided the operator interface and control of the data flow. A coincidence in the crossed scintillators gated by the -5 ms beam signal provided the 'start' signal for the Converter Module TDCs and 10 μs later produced an LSI interrupt and Converter Module 'read enable' signal. At the interrupt the monitoring ADCs, delay line MWPC TDCs and Converter Modules were read out. *MULTI* tested for the beam event conditions as defined in Section 4.1.1

¹This is referred to here as the '-5ms signal'.

and if accepted the event was written onto a 1600 bpi magnetic tape. The contents of the data event buffer are presented in Table 4.1 and the trigger logic is shown in Figure 4.1. A block diagram of the data acquisition system is presented in Figure 4.2.

The data was analysed using the OPAL vertex detector analysis code *CV* (version 2)[51] running as a subroutine in the OPAL 'Reconstruction of OPAL Physics Events' (*ROPE*) program environment[52]. Analysis was performed on a VAX (780 and 8250) operating under VMS and on an IBM 3090 (model 200) under VM/CMS. In general terms, analysis of the data consisted of the measurement of one quantity, such as the intrinsic resolution, as a function of a number of controlled parameters such as the gas gain or drift distance. The measurements were made for each beam track and accumulated in histograms with histogram management and statistical analyses performed using the CERN package, *HBOOKS*[53]. The fitting procedures in this package use the least-squares minimization technique. A block diagram of the basic analysis of a test beam event is illustrated in Figure 4.3.

4.1.3 Gas monitoring

The gases studied during the beam tests included CO₂-isobutane (80% – 20%) and a commercial grade premixture of argon-ethane (50% – 50%). The CO₂-isobutane was mixed in the pressure vessel using partial pressures. A schematic of the gas system is illustrated in Figure 4.4. Although the gas was not circulated while data were being collected, the entire volume of gas was recirculated once through the system at the begin of each gas fill. Forty-eight hours was the maximum time the gas was kept in the pressure vessel before a gas change but the 2.0 and 2.5 bar CO₂-isobutane data were collected with gas that was kept for less than thirty-six and twelve hours respectively. A plot of pressure/temperature and temperature versus time during the twelve hour 2.5 bar CO₂-isobutane gas fill is presented in

Figure 4.1: Vertex Detector Prototype Test Beam Trigger Logic

Figure 4.2: Block Diagram of Data Acquisition System for Vertex Prototype Test Beam Tests

Data Word	Contents
1	byte count
2	event type
3	run number
4	event no.(lo 16 bits)
5	event no.(hi 8 bits)
6	MULTI flags
7	pointer to variable length data
8	multiple beam count ($\pm 2 \mu s$)
9-12	delay line MWPC Lecroy TDCs
13-24	Lecroy 2249W ADCs 6 axial wires:start/stop
	RUN SCALERS
25	gated beams (lo 16 bits)
26	gated beams (hi 8 bits)
27	gated cosmoics
28	triggers
29	triggers with delay line MWPC hits
30	accepted triggers
31	triggers rejected by multiple event test
32	number of bursts
	BURST SCALERS
33	gated beams
34	triggers
35	delay line MWPC hits
36	accepted events
37	gated clock
	Lecroy LG8252 Scanning ADC
38-51	Bertan Supply Voltages
52	Pressure
53	Temperature
Variable Length Data	Converter Module data

Table 4.1: OPAL Vertex Detector Prototype Beam Tests Event Buffer

Figure 4.3: CV2 Vertex Prototype Event Analysis Procedure

Figure 4.5. This plot demonstrates that there was no measurable loss in gas density and reveals the range of temperature fluctuations during the gas fill. The RMS scatter in Pressure/Temperature measurements indicate that the gas density was known to be constant to within $\pm 0.15\%$.

Of some concern was the oxygen contamination of the isobutane as it has a large effect on electron attachment. To remove this contamination the isobutane was circulated through an activated copper filter (BASF R311) before mixing with the CO_2 . When this procedure was used there was no measureable loss in the charge (less than 4%) arriving at the anodes over the maximum drift distance of the axial cells. This is demonstrated by the plot of charge versus drift distance for the 2.5 bar CO_2 -isobutane (80-20) data which is presented in Figure 4.6. The charge was measured with the Lecroy 2249W ADCs.

Figure 4.4: Schematic of the gas system used for the OPAL Vertex Prototype tests

Figure 4.5: Pressure/Temperature and Temperature vs Time Measured during the 2.5 bar CO_2 -isobutane Gas Fill

Figure 4.6: Plot of charge vs drift distance measured at the end of the twelve hour 2.5 bar CO₂-isobutane gas fill

4.1.4 High voltage monitoring

There were three methods used to monitor the stability of the high voltage system used during the prototype tests. The first is a direct measurement of the Bertan supplies' monitoring voltages as a function of time. A study of the stability of the supplies was performed for three time domains. The first was over the period of a beam burst (2.8 s), the second over the period of a run (roughly 30 minutes to an hour) and the third was over a twenty-four hour period. This study demonstrated that the supplies were stable to better than $\pm 0.01\%$ over all three time domains. The relative error on a single high voltage measurement was $\pm 0.17\%$. The absolute voltages were measured at the $\pm 0.2\%$ level.

The second and third monitoring methods were sensitive to the stability of both the Lecroy ('anode end') supplies and the Bertan ('cathode end') supplies. The gas gain is a very sensitive function of the anode surface field² which, in turn is

²See Appendix B

Figure 4.7: Pulse sizes as measured with Converter Module ADC vs Time operating with argon-ethane (50-50) at 3.75 bar and an anode surface field of 520 kV/cm

sensitive to both the guard high voltage and the cathode voltages. A measurement of pulse size as a function of time was used to monitor the gas gain. A plot of pulse height using the ADC in the Converter Modules averaged over all wires in a sector versus time is presented in Figure 4.7. The pulse sizes were stable at the $\pm 2\%$ level. This translates into an anode surface field stability of $\pm 0.2\%$. Implicit in this measurement is the assumption that other effects that can reduce the pulse size as a function of time, such as outgassing of oxygen, were not present. It is difficult to rule out such an effect, so this measurement may be taken as evidence that any outgassing that may be present is lost in the $\pm 2\%$ statistical noise. With this in mind, the above measurement may be interpreted as an upper limit on the instability of the anode surface field.

Finally, the effective offset of the anodes is a strong function of the drift field. This is evident from calculations of the deflection as shown in Figure 4.8. This

Figure 4.8: Effective wire position as a function of drift field in the prototype as calculated using the electrostatics

dependence was parameterized as

$$x_{\text{wire}} = \text{endplate offset} + a \times e^{bE_d} \quad (4.1)$$

where with an endplate offset of $150 \mu\text{m}$ in the prototype $a = 1.00 \mu\text{m}$ and $b = 1.82 \text{ cm/kV}$. There is a small dependence on the anode surface field which provides a dominant systematic effect on the above parameterization. From Figure 4.8, it is apparent that as long as the anode fields are within $\pm 20 \text{ kV/cm}$ of the central values used in the calculations, the wire positions can be calculated to $\pm 10 \mu\text{m}$ using Equation 4.1. The relative anode positions are measured with beam tracks using a method described in Chapter 5 and can be monitored as a function of time. These

Figure 4.9: Change in bow plus endplate stagger as measured at $z=0$ using tracks as a function of time in the prototype with argon-ethane (50-50) at 3.75 bar

include measurements at different ϕ and θ and therefore there is the potential for some systematic problems associated with that. A plot of *Wire Position vs Time* is presented in Figure 4.9. The wire positions are measured at the level of $\pm 1\%$. If this uncertainty is entirely attributed to instabilities in the field it is equivalent to a drift field stability of $\pm 0.15\%$. It should be noted that these measurements assume that the drift velocity is constant. To ensure that this was so, the measurements were taken with the argon-ethane (50-50) (saturated velocity) gas over a period of time during which the gas did not change. As previously mentioned changes in the gas density and outgassing were undetectable during these measurements, therefore, the assumption that the velocity is constant is justified.

4.2 Electronics Evaluation

The noise and intrinsic timing resolution characteristics of the electronic system were measured. It is important to know the contribution of these two factors in order

to obtain a complete understanding of the resolution limitations of the detector.

Noise was measured with an oscilloscope viewing the analogue monitor output of the amplifier in the Converter Module. The noise was 0.4 mV RMS at that point in the system. With 3.75 bar argon-ethane(50-50) operating with an anode surface field of 520 kV/cm , which corresponds to a gas gain of 5×10^4 (see Appendix C), the mean pulse height for the beam particles was measured to be roughly 15 mV at the amplifier monitor output. The minimum pulse height that passed the discriminator's noise rejection threshold was 4 mV at the amplifier monitor output³.

These measurements indicated that the signal-to-noise ratio was greater than 10:1 in 3.75 bar argon-ethane for gas gains of 5×10^4 . The average signal-to-noise ratio was 38:1. Table 4.2 lists the mean pulse heights of particle tracks traversing the detector with $\phi=3.5^\circ$ and $\theta=90^\circ$ as measured with the Converter Module ADC. The table includes a survey of the fields and pressures used with argon-ethane(50-50) and CO_2 -isobutane(80-20) and includes the estimated minimum and mean signal-to-noise ratios. The gas gain is also quoted and is based on comparisons of the mean pulse heights of the tracks under the various operating conditions. The gas gain is obtained from these pulse heights using the ^{55}Fe gas gain measurements described in Appendix C.

The intrinsic timing resolution of the electronics was measured using a Lecroy ADC/TDC Tester (model 1976) operated in the START/STOP mode. This is essentially a programmable pulse generator that produces a pair of pulses separated by a programmed amount of time. The device was operated with a full scale time of 2400 ns and was scanned over the time range in steps of 200 ns . Lecroy specifications indicate that the RMS time jitter for this range is less than 320 ps , the full scale accuracy is $\pm 2\%$ and the linearity is 0.05% of full scale or 1.2 ns . As such, this

³This minimum pulse height corresponded to setting the discriminator's noise rejection threshold monitor at 40 mV . This may be directly compared with the timing discrimination thresholds discussed in Section 4.5.

Gas	Pressure (bar)	E_{anode} (kV/cm)	Gas Gain ($\times 10^4$) ($\pm$ sys. error)	<ADC> ± 0.1 (counts)	Signal-to-Noise Ratio	
					Minimum	Mean
argon-ethane (50-50)	3	475	7 ± 2	8.6	10:1	40:1
		480	8 ± 2	9.9	10:1	46:1
		490	9 ± 2	11.0	10:1	52:1
argon-ethane (50-50)	3.75	500	3 ± 1	5.0	10:1	23:1
		520	5 ± 2	8.1	10:1	38:1
		540	8 ± 2	11.5	10:1	54:1
CO ₂ -isobut. (80-20)	2	500	5 ± 2	1.7	7.5:1	8:1
		520	8 ± 4	2.8	7.5:1	13:1
		540	11 ± 6	4.0	7.5:1	19:1
		560	15 ± 8	5.4	7.5:1	25:1
CO ₂ -isobut. (80-20)	2.5	600	13 ± 7	5.6	7.5:1	26:1

Table 4.2: Pulse height from Converter Module ADC, gas gain and signal-to-noise ratio for operation with argon-ethane (50-50) and CO₂-isobutane (80-20)

is useful for evaluating resolution and integral linearity of the electronics. The distribution of vertex prototype TDC counts was fitted with a gaussian form for each Tester time. The mean is used to evaluate the linearity while the sigma is used as a measure of the intrinsic resolution of the electronics. A plot of a vertex prototype TDC vs TDC Tester time together with the residuals from a linear fit are presented in Figure 4.10. This demonstrates that the integral nonlinearity of the prototype TDC is less than the measurement errors. This sets the nonlinearity limit at 1.2 ns at $2 \mu\text{s}$. The resolution as a function of time is presented in Figure 4.11. Clearly, there is a degradation in electronics resolution as a function of drift time. During the prototype tests the Converter Modules servicing the 60 sense wires were installed in two separate crates each with its own clock. The resolution degradation shown in Figure 4.11 was worse than the degradation in the second crate. After the completion of the prototype tests the problem was traced down by the RAL electronics group to the TDC clock. The problem was rectified in the final version of the electronics.

Figure 4.10: Prototype RL1113 TDC (ns) vs Lecroy TDC Tester ΔT (ns)

Figure 4.11: Prototype RL1113 Resolution (ns) vs Lecroy TDC Tester ΔT (ns)

Finally, the differential linearity of the system (i.e. TDC channel-to-channel linearity) was evaluated. As described in Chapter 3 the Converter Module TDC provides a high precision measurement by interpolating between clock pulses. The interpolation provides the four least significant bits in the TDC word. To investigate the channel-to-channel interpolation linearity the TDC distributions of an argon-ethane run which had a uniform TDC distribution was studied. The TDC counts modulo 16 were histogrammed and deviations from a uniform distribution provided the differential non-linearity measure. An example of one such histogram is shown in Figure 4.12. The RMS deviation from the mean of the histogram bin contents in such a distribution was calculated for each wire in the two central axial sectors of the prototype. The contribution coming from bin-to-bin statistical fluctuations was removed and the nonlinearity is quoted as the ratio of the remaining bin-to-bin deviation to the mean number of entries in a bin. This was found to be $12.9 \pm 0.5\%$. Since the TDC bin width is 0.625 ns the differential non-linearity contributes a resolution degradation of $\pm 81\text{ ps}$ to the drift time measurement. For the hot gas this corresponds to $4\text{ }\mu\text{m}$ and such a value is swamped by the detector resolution.

4.3 r - ϕ Triplet Resolution and Z Time-Difference Resolution Studies

Studies of the intrinsic chamber resolution as a function of operating conditions and for various track orientations were performed. Some very loose cuts were applied that rejected hits not associated with the track⁴ and all tracks required to have a minimum of five hits.

Intrinsic resolutions in r - ϕ were measured using the raw drift times of three adjacent anodes having the same stagger sense: ‘unstaggered triplets’. These triplet

⁴These were roughly equivalent to the rejection of hits that were more than a millimetre away from the track.

Figure 4.12: Histogram of TDC counts modulo 16 in the prototype using argon-ethane over a uniform TDC distribution

resolutions are calculated from gaussian fits to the distribution of

$$\Delta_{trip} = v_{drift} \cdot \sqrt{2/3} \cdot [(t_1 + t_3)/2 - t_2]$$

The gaussian fit is less sensitive to the tails of the triplet distributions than the RMS and is preferred for that reason. The non-gaussian tails of resolution distributions are attributed to δ -ray hits[54]. Therefore, to permit the study of other limitations to the intrinsic resolution the gaussian fit resolution is preferred. The *triplet* resolution measurement is used because it eliminates systematic effects associated with chamber calibration. It is used as a means of obtaining an understanding of the intrinsic limitations of the detector and also provides a standard against which the final, calibrated resolution may be measured. The resolution of each of the eight unstaggered triplets in each of the six sectors of the prototype were measured. There were no measurable differences between sectors using the same time pick off method therefore the results from different sectors are combined in the presentation of data that follows.

The time-difference z measurement resolutions were measured from gaussian fits to the r - z track deviation distributions averaged over the wires in a sector. As the track fits include the wires in the fit, these measurements underestimate the point z resolution by roughly 14%.

The presentation of the data has been subdivided into the results for argon-ethane (50-50) and CO_2 -isobutane (80-20). For each gas the r - ϕ triplet and time-difference z resolutions are presented as a function of drift distance, ϕ , z and θ for two pressures. The coordinate system used is defined in Chapter 1 except that here ϕ refers to the *local* ϕ of a particular jet cell (i.e. the angle relative to the anode-guard plane). A plot of resolution as a function of the anode surface field at one of the pressures is also presented with the data separated into hits for which the wires whose resolution was measured was staggered towards the track ('near wires') and away from the track ('far wires'). See Figure 4.13. This distinction is made to enable crosstalk associated phenomena to be studied.

4.3.1 Argon(50)-ethane(50) test beam results

r - ϕ Triplet Resolution

When the chamber was operated with argon-ethane (50-50) at 3.75 bar the triplet resolution averaged over all drift lengths was measured to be between 60 and 70 μm for most angles as shown in Figures 4.15-4.18. A small improvement in the intrinsic r - ϕ resolution as the anode surface field increased is evident, as seen in Figure 4.14. The anode fields studied here correspond to gains between 3×10^4 and 8×10^4 . However, this improvement is entirely associated with a 14% improvement in the resolution of 'far' wires with no detectable improvement in the resolution of 'near' wires. A pulse on a 'far' wire has the potential of having residual crosstalk signals induced from the 'near' wires which produces fluctuations in the 'far' wire pulse shape. These 'near-far' effects are evident throughout the data. This result demonstrates

Figure 4.13: Definition of 'Near' and 'Far' Wires

that the drift time measurement is not limited by signal-to-noise considerations for near wires.

The resolution was degraded by approximately 7% when the pressure was reduced to 3.0 bar. The effects of diffusion are slight as evidenced by the very small change in resolution with drift distance. Therefore this improvement with pressure is attributed mainly to increased primary statistics and only partially to decreased diffusion.

A significant (25%) loss in the resolution for small beam ϕ angles relative to the anode plane was measured. This was attributed to residual crosstalk effects and will be discussed in detail in Section 4.4.

The z dependence of the resolution is quite complex. In Figure 4.17 the average of the near and far resolutions are plotted for $-45 < z < 0$ cm at $\phi = 3.5^\circ$. Less than

Figure 4.14: R- ϕ and Z intrinsic resolution as a function of anode surface field in argon-ethane (50-50)

Figure 4.15: R- ϕ intrinsic resolution as a function of drift distance in argon-ethane (50-50)

Figure 4.16: R- ϕ and Z intrinsic resolution as a function of ϕ in argon-ethane (50-50)

Figure 4.17: R- ϕ and Z intrinsic resolution as a function of Z in argon-ethane (50-50)

Figure 4.18: $R-\phi$ and Z intrinsic resolution as a function of θ in argon-ethane (50-50)

a 10% variation in the resolution is observed with such a measurement. However, when the data is separated into near and far wires and plotted from one end of the chamber to the other at two values of ϕ the complexity becomes apparent. A 25% worsening of the resolution is observed for far wires only but at only one end of the chamber, as seen in Figure 4.26. It will be demonstrated that this is attributable to crosstalk phenomena in Section 4.4.

As a function of θ the resolution is degraded by 15% when the track is oriented at an angle of 70° to the wire. It improves slightly at smaller θ . This dependence is associated with the spreading of the avalanches along the wire. With a track perpendicular to the wire the avalanches from all electron clusters occur at the same z . Space charge from avalanches of the early clusters tends to reduce the gain of later arriving clusters and therefore limits their influence on the pulse shape. When the track is no longer perpendicular to the wire the avalanches of later arriving clusters occur at slightly different z 's and therefore develop independently of the space charge effects of earlier clusters. The gain is higher and they have a greater influence on the pulse shape. Any pulse shape non-uniformities associated with fluctuations in the cluster sizes are amplified in the non-perpendicular tracks. This leads to the initial degradation in the resolution. The slight improvement in resolution that occurs at smaller values of θ is a consequence of the fact that the effective sample width is inversely proportional to $\sin \theta$. At smaller angles the number of primary interactions is increased and with this increase in the primary statistics the resolution improves.

A $60 \mu m$ resolution corresponds to a timing resolution of $1.1 ns$. Part of this can be accounted for by the intrinsic electronics resolution which was measured to be $0.5 ns$. Removing this in quadrature leaves a timing resolution of $\sqrt{1.1^2 - 0.5^2} = 1 ns$. It has been shown that noise and diffusion are not dominant contributions to the resolution and this points towards the pulse shape fluctuations as the dominant

Figure 4.19: Raw Z vs Beam Z Position for Argon(50)-Ethane(50) 3.75 bar

source of intrinsic resolution loss. All data presented so far is consistent with this hypothesis. Further support for this is presented in Section 4.5. It is quite evident that in this chamber the corruption of the signal created by crosstalk effects further degrades the resolution. This manifests itself as a signal-to-noise effect which is minimized by increasing the original chamber signal.

Time-Difference Resolution

The measurement of the time-difference resolution depends on the calibration of the conversion from time-difference to position along the wire. This calibration was performed by scanning the beam over the length of the chamber and measuring the mean of the raw time-difference measurement as a function of the beam z . The 'STOP' end (negative z) has a time-difference of 10 while at the 'START' end (positive z) it is 54. A sample of this calibration is presented in Figure 4.19 A linear function that describes this dependency is :

$$z = -71.22 + 2.1088 \times (\text{time difference}).$$

This is not entirely adequate at the ends of the chamber, but for quoting resolutions measured away from the ends of the wires it is sufficient. The resolution of the time-difference measurement is strongly dependent on whether the wire is 'near' or 'far'. Figure 4.14 reveals that the resolution on the 'near' side of a wire is roughly 2 cm while on the 'far' side it is 3.4 cm or 70% worse than for the 'near' side. The propagation time down the anode wire is roughly 5 ns; therefore these measurements correspond to timing resolutions of 100 ps and 170 ps respectively.

Trends in the time-difference z resolution data suggest that the time-difference measurement is limited mainly by noise. This is not surprising since the pulse shape at either end of the wire is similar for a given event and the constant fraction discrimination method effectively reduces time slewing effects. An increase in the anode surface field from 500 to 540 kV/cm (Figure 4.14), which corresponds to an increase in gain by a factor of two, results in a 15 – 20% improvement in the time-difference resolution. This effect is also reflected in the dependence of the time-difference on θ (Figure 4.18). With a decrease in θ the pulse size increases and the resolution decreases.

The data presented so far has not revealed the full complexity of crosstalk in this system. In addition to a degradation in the 'far' side z resolution there are systematic shifts of between 5 and 7 cm for 'near' and 'far' side z measurements on the same wire. These effects will be dealt with in Section 4.4.

4.3.2 CO₂(80)-isobutane(20) test beam results

r - ϕ Triplet Resolution

The introduction into the chamber of a gas having a low drift velocity was advantageous because the spatial resolution is proportional to the drift velocity for a fixed timing resolution. This is evident in the CO₂-isobutane (80-20) operation. When

operated at 2.5 *bar* the triplet resolution averaged over all drift lengths was measured to be between 20 and 30 μm for all angles as shown in Figures 4.22-4.25. As in the argon-ethane a small improvement in the intrinsic $r\text{-}\phi$ resolution as the anode surface field (Figure 4.21) increases is entirely associated with a 12% improvement in the resolution of 'far' wires with no detectable improvement in the resolution of 'near' wires. These anode fields span gas gains from 5×10^4 to 1.5×10^5 .

The $r\text{-}\phi$ resolution as a function of drift distance is shown in Figure 4.22 for this gas. The resolution at 2.5 *bar* for distances greater than 2 *mm* was typically 25 μm . Within 2 *mm* of the anode wires the drift velocity increases with the electric field and a corresponding degradation in the resolution was observed. Near the anode wire the resolution approached 80 μm for 2.5 *bar* operation and over the first 2 *mm* the average resolution was 43 μm .

A scan of pressure, shown in Figure 4.20, demonstrates that the timing resolution becomes marginally worse as the pressure increases. Maintaining a constant drift field while increasing the pressure results in an improvement in the spatial resolution because the velocity varies inversely with pressure. The worsening timing resolution with increasing pressure is a consequence of the fact that for a field of 3.2 *kV/cm* in the 2 to 2.5 *bar* pressure region the diffusion decreases slightly [55, page 122] as E/P increases. The effects of diffusion are most evident in the plot of resolution against drift distance (Figure 4.22). Care must be taken to include the decrease in the electronic resolution (Figure 4.11) in the interpretation of these plots. After accounting for such effects, a fit to σ^2 vs drift distance yields the result that diffusion accounts for $20 \pm 2 \mu\text{m}/\sqrt{\text{cm}}$ in both the 2.0 and 2.5 *bar* data. At a distance of 5 *mm* this leaves a remaining intrinsic timing resolution of 1.4 *ns* to be accounted for. Part of this is in the electronics which can be stripped off leaving a residual resolution of 1.1 *ns*. This is dominated by pulse non-uniformity effects and primary statistics variations.

Figure 4.20: $R-\phi$ intrinsic resolution as a function of pressure in CO_2 -isobutane (80-20)

Figure 4.21: R- ϕ and Z intrinsic resolution as a function of anode surface field in CO_2 -isobutane (80-20)

Figure 4.22: R- ϕ intrinsic resolution as a function of drift distance in CO₂-isobutane (80-20)

Figure 4.23: R- ϕ and Z intrinsic resolution as a function of ϕ in CO₂-isobutane (80-20)

Figure 4.24: R- ϕ and Z intrinsic resolution as a function of Z in CO₂-isobutane (80-20)

Figure 4.25: $R-\phi$ and Z intrinsic resolution as a function of θ in CO₂-isobutane (80-20)

An r - ϕ resolution degradation of less than 15% was observed when studied as a function of θ with the worst occurring at 70° as in the argon-ethane. There is only a slight dependence of the resolution on the ϕ angle of the tracks relative to the anode plane with the best resolution occurring at a ϕ of 2° . There is no significant dependence of the resolution on z .

Time-Difference Resolution

As with the argon-ethane, the time-difference measurement is strongly dependent on the gas gain and is significantly different for 'near' and 'far' sides of the wire. The best resolution was measured at the maximum gas gain studied (1.5×10^5) where the anode surface field was 560 kV/cm and the pressure was 2.0 bar. At this field the resolution was 3.4 cm for the 'near' side and was 4 cm or 22% worse for the 'far' side. The 'near' side resolutions are roughly 70% worse than the resolutions measured in the argon-ethane while the 'far' side resolutions are nearly the same. The 3.4 cm measurement corresponds to a timing measurement of 180 ps.

The loss in resolution is a consequence of the fact that the pulse heights are lower because of the reduced number of primary electrons (the pressure is lower for the CO₂-isobutane data) and because the rise times of the pulses in CO₂-isobutane (80-20) are longer than in argon-ethane because of the difference in electron drift velocity. The net effect is a decrease in the timing signal-to-noise when a gas with a low drift velocity is used. This is the same effect that produces the improvement in resolution as the gas gain increases.

The improvement in the 'near-far' asymmetry in this gas as compared with argon-ethane is a reflection of the fact that the crosstalk between adjacent wires is not as severe. This is partly associated with the fact that in a gas with a low drift velocity and for values of ϕ less than 5° at $z=0$ (for these wire deflections) the pulses do not arrive within a small enough time of each other. As a consequence

the severity of the crosstalk is much lower than in argon-ethane.

4.4 The Effects of Crosstalk in the Prototype

Many systematic trends in the response of the detector cannot be accounted for unless the effects of crosstalk are taken into consideration. Crosstalk effects refer to the distortion of the pulse shape that occurs on a given wire due to the superposition of the actual signal and induced signals originating on nearby wires. The main crosstalk signals come from the motion of positive ions from an avalanche on an adjacent anode, as described in Chapter 3. An attempt to compensate for this was made in the prototype but the compensation was not ideal and residual crosstalk was expected. Crosstalk can also originate from the reflections of pulses transmitted along unterminated chamber wires. In the prototype only the anode and guard wires were properly terminated. There was no attempt to terminate the cathodes and field wires. In this section the data are presented that demonstrate that these crosstalk effects provide an explanation for the observed trends in the chamber response.

It has been demonstrated that the resolution for particle tracks on the 'far' side of a wire is worse than on the 'near' side. This is evident in the plots of resolution as a function of z and ϕ when the 'near' and 'far' side data are separated. See Figures 4.26 to 4.28.

If crosstalk is the explanation for these effects the magnitude of the 'near-far' resolution asymmetry should depend on the difference in the arrival time of a 'near' and 'far' hit:

$$\Delta_{\text{Arrival}} = \frac{2 \times \Delta X \pm 0.5308 \text{ cm} \times \tan \phi}{\text{Drift Velocity}}$$

ΔX is the distance between an anode wire and the guard plane. It is the sum of the geometrical offset on the comb and the z -dependent offset from the electrostatic deflection of the wire. Δ_{Arrival} is a double-valued quantity because the crosstalk

Figure 4.26: Near and Far Side $r-\phi$ Resolution as a Function of Z in argon-ethane (50-50)

Figure 4.27: Near and Far Side $r-\phi$ Resolution as a Function of ϕ in argon-ethane (50-50)

Figure 4.28: Near and Far Side $r-\phi$ Resolution as a Function of (a) ϕ and (b) Z in CO₂-isobutane(80-20)

signal can be associated with the signal on a wire on either side of the affected wire. In CO₂-isobutane only one of the adjacent wires has a signal close enough in time to its neighbor to produce crosstalk effects. However, in argon-ethane, with a much higher drift velocity, the anode wires on both sides can contribute interference. Based on this argument, the effects of crosstalk ought to be worse in argon-ethane than in CO₂-isobutane. This is in fact what was observed.

The value of $\Delta_{Arrival}$ at which the most significant interference will occur cannot be reliably predicted. Heuristically, however, one can argue that the interference to a timing measurement is greatest when the maximum of the early signal is coincident with the timing measurement of the later signal. Therefore the worst 'near-far' asymmetry is expected to occur when $\Delta_{Arrival}$ is roughly equal to the 100% rise time of the pulse. In the 3.75 bar argon-ethane data at $z=0$ the worst 'far' $r-\phi$ resolution occurs for $\phi=0^\circ$ tracks and corresponds to a $\Delta_{Arrival}$ of 18 ns. This is consistent with the rise time statement.

A more serious problem in the detector is the splitting of the time-difference z measurement. The mean of the 'far' side z -deviations are up to 7 cm (or 350 ps) offset from the mean of the 'near' side deviations for a given set of tracks. For offline analysis at OPAL this is only a calibration problem. But the time-difference will be used in the OPAL hardware trigger where no 'near-far' time-difference calibration can be performed. This 'z-splitting' therefore would limit the effectiveness of the vertex z_0 constraint in the OPAL trigger which was discussed in Chapter 2. A series of plots of the difference between the means of 'near' and 'far' side deviations is presented in Figures 4.29 and 4.30. The pressure is indicated as a variable but only appears because the operating uniform drift field and hence anode wire bow depends on the pressure. These plots suggest that the origin of the 'z-splitting' is crosstalk. The basic trend in the argon-ethane data is that the 'z-splitting' is worse for small ϕ and large bows, just as with the $r-\phi$ resolution. When plotted

against $\Delta_{Arrival}$, as in Figure 4.29, it becomes clear that the maximum splitting for the 3 and 3.75 bar data occurs for values of $\Delta_{Arrival}$ between 16 and 20 ns. This is consistent with the value for maximum r - ϕ resolution loss. At lower pressure the anode bow is less and the effects are less pronounced. Moreover, they are shifted to shorter times. It is assumed that this is associated with a change in pulse shape that accompanies the changes to the isochrones at the lower pressures. In CO₂-isobutane, with its slow drift velocity, longer pulse risetime and only one wire contributing to the crosstalk, the splitting is significantly less and occurs at a later time: between 25 and 40 ns.

The asymmetries in the response of the detector to the side of the anode plane from which a pulse originates are strongly correlated with $\Delta_{Arrival}$. This strongly suggests that these effects are associated with crosstalk between adjacent wires. However, the nature of crosstalk originating from the motion of positive ions from an avalanche on an adjacent anode wire cannot account for the 'z-splitting' effect.

Recall that the value of z was obtained by measuring the difference of the arrival time of pulses from the *same* avalanche that are transmitted to opposite ends of the anode wire. The z-splitting crosstalk could not be associated with motion of positive ions at adjacent anodes because the pulses at opposite ends of the chamber have the same shape corresponding to the superposition of the actual pulse and the opposite polarity induced pulse. The time-difference measurement would still yield the same result regardless of the presence of adjacent anode positive ion motion.

The 'z-splitting' implies that for a 'far' wire the signal at one end of the chamber has been modified by crosstalk differently from that at the opposite end. That is, there is an end-to-end asymmetry in the crosstalk. The source of this asymmetry was traced down to a problem with the termination of the cathode and field shaping wires. As mentioned above, there was no attempt to properly terminate these wires. However, the high voltage distribution system included a filtering capacitor mounted

Figure 4.29: Z-Splitting effect in the prototype with argon-ethane

Figure 4.30: Z-Splitting effect in the prototype with CO₂-isobutane

at both the high and low ends of the cathode and field ring resistor chains but only at one end of the chamber. In the axial cells of the prototype these capacitors were mounted in such a way as to provide good cathode termination but only at one end of the chamber. This introduced a difference in the crosstalk associated with wire termination between the two ends of the chamber and can account for the 350 ps 'z-splitting' effect.

Further support for this explanation lies in the fact that the r - ϕ resolution has a z -dependent 'near-far' asymmetry as can be seen in Figure 4.26. The high voltage filtering capacitors were located at the positive z end of the chamber. It is apparent from the plot that the 'near' and 'far' wires have similar resolution near the cathode terminated end but at the unterminated end the resolution of the 'far' wires is degraded by more than 10%.

These crosstalk studies suggest that implementation of the correct termination of all wires in the chamber would improve the detector performance. The final detector design has included proper termination of the cathodes.

4.5 Timing Discrimination Studies

The resolution measurements have been shown to be consistent with the hypothesis that pulse shape fluctuations are a dominant practical limitation to the drift time resolution while noise is the factor dominating the limit to the time-difference measurement. A series of studies using two different time pickoff techniques (constant fraction with a noise veto threshold and leading-edge timing threshold with a noise veto threshold) were undertaken to find the optimal timing discrimination method.

The constant fraction discriminator provides a means of eliminating pulse height slewing effects by timing on the same *fraction* of the pulse height for all pulses. It is implemented in the vertex prototype electronics by splitting the analogue pulse

into two separate pulses. One is delayed by some time comparable with half the rise time while the other is attenuated by a factor of two. The two pulses are then compared and the discriminator fires at the crossing point of the two derived pulses (see Figure 4.31). A noise threshold is used to veto pulses that have a very small amplitude.

It is clear that, although this discriminator is relatively insensitive to pulse height when the pulse shapes are uniform, it cannot provide a consistent timing measurement if the rise time is variable. Unfortunately, the pulses produced by charged particles in a proportional counter do not have a uniform rise time or shape, therefore this technique is not necessarily optimal for drift time measurements. This technique can be adapted to decrease the sensitivity to pulse shape by making the delay between the two derived pulses as short as possible. By so doing, the timing is performed on the earliest part of the pulse which is the time regime that is the least sensitive to the global shape properties of the pulse. In practice, the smallest time that can be used is set by the noise in the system. It should be noted that when performing the end-to-end time-difference measurement the pulses that arrive at either end of the wire will have a different size but the same shape. This is the situation for which the constant fraction discriminator was designed.

The leading-edge threshold discriminator provides a means of timing on the earliest part of a pulse. A second threshold is provided here also to veto noise pulses. Provided the timing threshold can be set low enough, this technique has the potential of providing timing that is independent of the shape of the pulse and relative insensitivity to the pulse size. The limitation in achieving this is effectively one of signal-to-noise. If the timing threshold is too low the timing resolution is degraded by noise while if it is too high the measurement becomes sensitive to the pulse height and shape.

During these studies the length of the delay in the constant fraction discrim-

Figure 4.31: Schematic diagram of the time pickoff methods used in the prototype timing discrimination studies

inator was set at either 5 ns or 7.5 ns . The timing threshold of the leading-edge threshold discriminator was varied between 4 and 25 mV where below 4 mV the noise overcame the measurement. The noise veto threshold was set at 40 mV which was roughly equal to 10 times the RMS noise level as discussed in Section 4.2. Figure 4.32 to 4.35 and Table 4.3 present some of the resolution measurements for the various discrimination configurations in both the CO_2 -isobutane and argon-ethane.

In Figure 4.32 the drift time and time-difference measurements are presented as a function of ϕ for timing thresholds set at 10 and 20 mV and, for comparison, the resolutions using the constant fraction delay time of 5 ns is included. Although there are only marginal differences in the drift time resolutions one can conclude that the lower timing threshold (10 mV) provides improved resolution over the higher timing threshold (20 mV). Also, the 10 mV timing threshold (or 2.5 times the noise level) and the 5 ns constant fraction discrimination provide equivalent drift time resolutions. When comparing the time-difference measurements the differences are more dramatic and in the opposite direction. In this case the lower timing threshold provides significantly *worse* resolution than the higher timing threshold. The constant fraction measurement provides equivalent resolution to the best timing threshold measurement. These results imply that the time-difference measurement is limited by noise: a lower timing threshold is more sensitive to noise than a higher threshold. The fact that a marginal improvement in the drift time measurement is attained by using a lower threshold tends to suggest that the more global pulse shape fluctuations are limiting this measurement. In that case, by decreasing the timing threshold the measurement is made less sensitive to such pulse shape nonuniformities.

Comparison of the 10 mV timing threshold and 5 ns constant fraction resolutions as a function of anode surface field (Figure 4.33) reveals some interesting trends that add support to the above interpretation. The drift time measurement

Figure 4.32: Varying Leading-Edge Thresholds in CO_2 -Isobutane

improves with increasing signal size for the threshold measurement. Increasing the gas gain is roughly equivalent to decreasing the threshold in leading-edge threshold measurement. As a consequence, the drift time resolution improves with higher gain as the measurement is made less sensitive to pulse shape. On the other hand, if the time-difference measurement is already noise limited as suggested above, no improvement is expected with increased gain. This is what is observed.

The constant fraction measurement has different characteristics. Increasing the gain does not improve the drift time measurement but significantly improves the time-difference measurement. This is a consequence of the fact in this measurement the increased gain is not equivalent to a decreased threshold: the timing is always performed at the same fraction of the pulse height. But by increasing the gain the slew rate increases and this increases the immunity to noise. The measurements confirm that by increasing gas gain the measurement does not become less sensitive to shape fluctuations (the $r\text{-}\phi$ resolution is constant) but does experience an improved signal-to-noise ratio (the time-difference measurement improves).

One way of further investigating the origins of the resolution limitations is to change the delay time in the constant fraction discriminator. A shorter delay time is equivalent to a lower leading-edge timing threshold. As demonstrated above, this implies that a shorter delay time should provide an improved drift time measurement but a worse time-difference measurement. A set of measurements for two constant fraction delays (5 and 7.5 ns) was performed with the chamber operating with both CO₂-isobutane at 2.5 bar and argon-ethane at 3.75 bar with the results presented in Figures 4.34 and 4.35 respectively. Although the differences were slight, there was an improvement in the drift time measurement when the shorter delay is used and an observable degradation in the time-difference measurement when the shorter delay is used. This provides further confirmation for the above statement that shape fluctuations limit drift time measurements and noise limits the

Figure 4.33: Varying anode surface field for constant fraction and leading-edge threshold timing in CO₂-Isobutane

Discriminator	r- ϕ Triplet Resolution (μm)		Time-Difference z Resolution (cm)	
	near	far	near	far
constant fraction 5ns Delay	59.2 ± 0.4	62.5 ± 0.4	3.0 ± 0.1	4.5 ± 0.2
leading-edge 15 mV Threshold	48.6 ± 1.1	80.4 ± 2.9	6.3 ± 0.6	8.9 ± 0.7
leading-edge 10 mV Threshold	47.0 ± 1.1	87.4 ± 3.2	5.9 ± 0.4	9.8 $\pm 1.$
leading-edge 4 mV Threshold	49.2 ± 0.8	86.6 ± 7.7	5.9 ± 0.7	9.3 ± 0.8

Table 4.3: Varying Leading-Edge Thresholds in 3.75 bar Argon-Ethane with $z=0$, $\theta = 90^\circ$, $\phi = 5^\circ$ with an anode surface field of 520 kV/cm

time-difference measurement.

The data presented in Table 4.3 confirms yet again these assertions. The near-wire r- ϕ resolutions are significantly improved when the leading-edge threshold method is used with a low threshold. This also accounts for the improved r- ϕ resolutions when a 5 ns delay is used in the constant fraction discriminator instead of a 7.5 ns delay when both CO₂-isobutane and argon-ethane are studied. One other feature of this data is also significant: the far-wire leading-edge threshold resolution is 50% worse than the far-wire constant fraction resolution. This supports the statement that the far-wire resolution is poor because of the irregularity in the crosstalk pulses. The low threshold lead-edge discriminators are expected to be more sensitive to such effects and this is what was observed. The data in Table 4.3 demonstrate yet again that the time-difference measurements are limited by the noise. The z resolution is degraded as the timing threshold is turned down in the leading-edge discriminator and when the delay is reduced in the constant fraction discriminator.

These studies confirm that the pulse shape fluctuations are a dominant limitation to the r- ϕ resolution and that noise is the limit to the time-difference resolution.

Figure 4.34: Varying Constant Fraction Delays in CO₂-Isobutane(80-20)

Figure 4.35: Varying Constant Fraction Delays in Argon-Ethane(50-50)

4.6 Multihit Studies

The vertex electronic readout is designed to provide drift time, time-difference and ADC data for up to 15 hits on each wire for every 'START' signal. The detector system was designed to be able to resolve hits that occur within 2 mm of each other. The purpose of these multihit studies was to measure the resolving distance between two hits and to investigate the factors that limit the two particle separation resolution.

Before a second pulse can be digitized the height of the first pulse must fall below the upper noise veto threshold of the discriminator. For this reason, the length of time it takes for the first pulse to fall off dictates the minimum distance between hits that can be resolved. A very simple method of measuring this 'minimum resolving time' takes advantage of the fact that for some fraction of pulses the shape of the pulse tail varies enough to re-fire the discriminator. The shape fluctuations are associated with noise and the arrival of later ionization electron clusters. The length of the pulse tail is dominated by the isochrone structure which in turn depends on the electrostatics and electron drift velocity. The shortest possible re-fire time for a given pulse is a measure of the minimum resolving time for that pulse. A scatter plot of *Second Hit TDC vs First Hit TDC* when only a single track is present in the sector demonstrates this technique. To avoid pattern recognition inefficiencies the presence of 'one track' in an axial sector is *defined* as a beam event having :

$$4 < \text{No. of Hits} < 16.$$

Two track beam events are defined as those having

$$12 < \text{No. of Hits} < 28.$$

These definitions allow for up to 4 re-fired wires per track per sector. Figure 4.36 is an example of such a plot in which all wires in a particular sector are included

for 'one track' beam events in argon-ethane(50-50). A histogram of the difference between the first and second hits in a 'one track' event is shown in Figure 4.37. The peak in this distribution is defined as the 'minimum resolving time'.

Measurements were made using 3.75 bar argon(50)-ethane(50) with a 3.2 kV/cm drift field and 520 kV/cm anode surface field and 2.0 bar CO₂(80)-isobutane(20) with the same fields. The argon-ethane had a minimum resolving time of 40.4 ± 2.7 ns while in the CO₂-isobutane it was 56.1 ± 2.6 ns. This is qualitatively consistent with the fact that CO₂-isobutane has the lower drift velocity and therefore a longer pulse. These times translate into two hit resolved minimum distances of 2.1 mm for the argon-ethane and 0.73 mm for the CO₂-isobutane.

The 'minimum resolving time' is not the most significant figure of merit that can be used to describe the two hit resolution of the detector. The efficiency of the system to detect the second hit may be poor at the 'minimum resolving time'. Therefore, the efficiency as a function of the distance between two hits was measured for beam events having two tracks in a sector. As described in Section 4.1.1 the two track events were produced in the interactions between 45 GeV pions and a paraffin target. Efficiency was measured by selecting a series of target beam events with the following attributes:

- At least 4 wires in an axial cell had two hits.
- No wires in that cell had more than 2 hits.
- A line was fit to each set of hits. If the χ^2 was excessively high, the event was not used.
- If the extrapolated drift distance of the fitted lines at wires 1 and 12 exceeded 0.8 cm the event was not used.

This defined an event having two tracks with no geometric efficiency biases. The ef-

efficiency was calculated by histogramming a variable that was set to '1' if a particular wire was hit and '0' otherwise. The arithmetic mean of this variable was calculated and plotted as a function of the difference between the first and second hit drift distances as determined by the fitted lines. This was done for argon-ethane (50-50) at 3.75 bar and CO₂-isobutane at 2.0 bar. The plots are presented in Figure 4.38.

In both the argon-ethane(50-50) and CO₂-isobutane(80-20) the second hit efficiency reaches 0.5 when the hits are separated by roughly 2 mm. But the cool gas has an efficiency of 0.4 when the hits have a 1 mm separation while the hot gas has an efficiency less than 0.2 at 1 mm. The efficiency of the first hit for the same conditions is 0.99 for both hot and cool gases.

The second hit efficiency is degraded by the tails of the first pulse associated with the first hit's late arriving electrons. A large and long tail from the first pulse superimposed with the second pulse can be so high that the discriminator is unable to re-fire. This results in a reduced efficiency for the second pulse.

The second *track* efficiency depends on both the second *hit* efficiency and the minimum number of hits required to define a track. If 4 hits are required to define a track then the second tracking efficiency is 0.93 when the tracks are separated by 2 mm. This is reduced to 0.81 if 5 hits are required to define a track. In the cool gas the second track efficiency for a 1 mm separation is 0.77(0.56) when 4(5) hits are required to define the track.

The resolution of the second hit, measured using track deviations, is plotted as a function of time between hits in Figure 4.39. The resolution is degraded when the difference between hits is less than 3 mm. This is consistent with expectations based on the isochrone properties of the detector. The late arriving clusters do not necessarily re-fire the discriminators, they are expected to interfere with the following hits and produce a loss in resolution.

Figure 4.36: Second Hit TDC vs First Hit TDC in 3.75 bar argon-ethane(50-50)
 $E_a = 520 \text{ kV/cm}$, $E_d = 3.2 \text{ kV/cm}$

Figure 4.37: Second Hit TDC - First Hit TDC in 3.75 bar argon-ethane(50-50)
 $E_a = 520 \text{ kV/cm}$, $E_d = 3.2 \text{ kV/cm}$

Figure 4.38: Second Hit Efficiency as a Function of Separation Between Hits

Figure 4.39: Second Hit Resolution as a Function of Distance Between Hits of Double Track Events

4.7 Stereo Cell Z Resolutions

To conclude this chapter, the results of a study of the z resolution as measured using the stereo cell matching is presented. An axial cell-stereo cell 4 parameter (2 parameters in the r - ϕ plane and 2 in the r - z plane) joint track fit was performed using a procedure based on the Lagrange multiplier method and is described in detail in Reference [56]. A calculation of the z coordinate of each axial and stereo wire along the track is provided by the fitting procedure. It will be demonstrated here that the z resolutions obtained using the stereo cell information with this joint axial-stereo fit is consistent with the intrinsic r - ϕ resolution of the detector.

In the simplest consideration with an assumption of absolute knowledge of r - ϕ , the resolution of z measured with a stereo wire having a stereo angle α_s , is:

$$\frac{\sigma_{r\phi}}{\sin \alpha_s}.$$

In the prototype tests only the vertex axial cell was used to determine the r - ϕ coordinate in the stereo cell. Therefore an additional term associated with the extrapolation uncertainty into the stereo cell must be included when examining the stereo cell resolution in these tests. This extrapolation error averaged over the six stereo wires in the prototype is:

$$1.16 \frac{\sigma_{r\phi}}{\tan \alpha_s}.$$

In the vertex detector α_s is small (roughly 4°) so the resolution from both sources may be combined as:

$$1.53 \frac{\sigma_{r\phi}}{\alpha_s}.$$

Finally, because the joint fit distributes the z information over all axial and stereo wires, the z resolution as calculated from a known r - ϕ resolution must be multiplied by roughly

$$\sqrt{\frac{\text{total no. of wires}}{\text{no. of stereo wires}}}$$

Figure 4.40: Scatter Plot of Stereo z vs MWPC Z for 2.00 bar CO_2 -isobutane(80-20)

or $\sqrt{18/6}$ before comparing them with the value obtained from the joint fit. To summarize, the z resolution expected from the joint fit is:

$$\sigma_z = 1.53\sqrt{3}\frac{\sigma_{r\phi}}{\alpha_z}.$$

As described in Section 4.1 a delayline MWPC was located down stream of the prototype detector. This MWPC had single-hit readout in the two dimensions transverse to the beam with a spatial resolution of 0.3 mm . Since readout was provided along the z direction and the beam profile extended over several centimetres this device provided a means of independently evaluating the z resolution of the vertex detector. Tracks having $\tan\theta < 0.1$ were selected from events with single tracks and the tracks' stereo z measurements from the joint fit were compared with those of the delay line MWPC. A scatter plot of *Stereo Wire Z vs. Delayline MWPC Z* when 2.0 bar CO_2 -isobutane was used in the prototype is presented in Figure 4.40.

The deviations of the z on each stereo wire from the expected z as determined

Figure 4.41: Stereo resolution from a comparison of the stereo z measurements and delay line MWPC measurements in argon-ethane(50-50) and CO₂-isobutane(80-20)

by the delay line MWPC z and a linear fit to *Mean Stereo Z vs Delayline MWPC Z* were measured. Gaussian fits to the distributions of the deviations yielded a measure of the stereo z resolution. Typical plots of such distributions are shown in Figure 4.41. For 3.75 bar argon-ethane the standard deviation averaged over the six stereo wires was $2.18 \pm 0.09 \text{ mm}$. For 2.0 bar CO₂-isobutane with a drift field of 3.2 kV/cm the average z-resolution was $1.45 \pm 0.06 \text{ mm}$.

Because these prototype detector resolution measurements were obtained by comparing the z measurement with an independent detector that had a higher z resolution they can be used to examine the absolute $r\text{-}\phi$ resolution of the stereo cells. From the above discussion:

$$\sigma_{r\phi} = \frac{\sigma_z \alpha_s}{1.53\sqrt{3}}.$$

For 3.75 bar argon-ethane the $\sigma_{r,\phi}$ from these z measurements is $57.4 \pm 2.4 \mu m$. For 2.0 bar CO₂-isobutane the absolute stereo cell r - ϕ resolution was $38.1 \pm 1.6 \mu m$.

The fast gas resolution is consistent with the triplet measurements of the r - ϕ resolution. This is an indication that the most significant systematic effects associated with saturated gas operation have been properly dealt with in the calibration procedure. This includes such things as geometric and electronic calibrations as well as the time-to-distance calibration. An extensive discussion of these calibration issues is presented in Chapter 5.

For the unsaturated gas the r - ϕ resolution is worse than the triplet resolution measurements. The triplets provided an intrinsic r - ϕ resolution of $30 \mu m$ under these conditions. The resolution degradation is a reflection of the residual systematic uncertainties that have not been fully accounted for in the calibration of the unsaturated gas time-to-distance relation⁵. This was not unexpected because the values of the electric field used in calibrating the time-to-distance relation for this study were based on the electrostatic fields in an axial cell only. The fields in the stereo cell would be slightly different because of the different geometry. It is encouraging that the absolute resolution is not entirely dominated by fine-tuning of the unsaturated gas time-to-distance relation and tends to suggest that the calibration technique is reasonably robust. The contribution of the residual systematic contributions can be quantified by subtracting the intrinsic resolution obtained from the triplet measurement in quadrature from the absolute measurement obtained from the stereo z measurement:

$$\sqrt{(38 \mu m)^2 - (30 \mu m)^2} = (23 \mu m)^2$$

This indicates that the time-to-distance unsaturated gas systematics uncertainties are at the 20 to 25 μm level.

⁵The time-to-distance calibration procedure is described fully in Chapter 5

The contribution of stereo z measurements to the determination of the z coordinate of the primary vertex can be evaluated under several scenarios in which different detectors contribute different pieces of information. Assuming a fast gas resolution of $50 \mu m$, the joint track fit yields a z impact parameter resolution of $0.6 cm$ at the interaction vertex when only the vertex detector is used (with no multiple scattering contribution)[56]. This is consistent with the z impact parameter resolution obtained when one assumes only z measurements on the stereo wires with the z resolution at each wire equal to

$$\sigma_z = 1.53 \frac{\sigma_{r\phi}}{\alpha_s}.$$

This is the case if only the axial part of the vertex detector is used to specify $r\phi$ in the stereo cells.

If these six stereo wire z measurements are combined with the measurements from the OPAL Z chambers (which have a point z resolution of $0.03 cm$) the impact parameter resolution is $0.047 cm$. However, if the OPAL Jet chamber (which has a point $r\phi$ resolution of $0.013 cm$) is used with the vertex axial cell to determine an interpolated $r\phi$ value in the stereo cell this resolution improves to $0.032 cm$ for high momentum tracks.

Table 4.4 provides a summary of the expected resolution of the z impact parameter with different assumed $r\phi$ resolutions. The case when only the axial cells of the vertex detector contribute to the stereo $r\phi$ determination and the case when the Jet chamber also contributes are separately treated. From this simple analysis it is apparent that in the limit of no multiple scattering, the z impact resolution improves by one third simply by including the Jet chamber in the determination of the stereo $r\phi$ coordinates. If a cool gas is used the z impact parameter resolution can be as low as $240 \mu m$ for high momentum tracks.

Vertex $r\text{-}\phi$ Resolution (cm)	Z impact parameter resolution (cm)	
	Stereo $r\text{-}\phi$ from Vertex Axial cell only	Stereo $r\text{-}\phi$ from both Vertex Axial and Jet Chambers
0.0038	0.036	0.024
0.0057	0.054	0.036
0.0070	0.066	0.044

Table 4.4: Z vertex impact parameters with and without the Jet chamber contributing to the $r\text{-}\phi$ extrapolation into the stereo cell. No multiple scattering is considered.

4.8 Summary

Drift time measurements using a hot gas with a saturated drift velocity have been shown to be limited by the fluctuations in the shape of the pulses. It was demonstrated that neither diffusion nor the electronics provided major degradation to the resolution. The shape fluctuations contributed 1 ns to the timing resolution. Use of a threshold time pick-off method demonstrated that the resolution could be improved by timing just above the noise. By timing at the earliest part of the pulse the influence of shape fluctuations are minimized. This result confirmed the hypothesis that fluctuations limit the drift time measurement as predicted by the Monte Carlo calculations discussed in Chapter 3.

In the case where there was significant crosstalk (i.e. 'far' wires) the shape fluctuations were worse resulting in poorer resolution but this could be made less significant by increasing the signal size. Use of a threshold time pick-off was greatly limited by the presence of crosstalk and provided further evidence that the crosstalk phenomena could be considered a signal-to-noise limitation to the intrinsic resolution.

Use of a cool gas provided one method for overcoming the limitation of pulse shape fluctuations. The timing resolution in the cool gas was slightly worse than in the hot gas but the gain in spatial resolution provided by the reduced drift velocity

resulted in a factor of two improvement in intrinsic spatial resolution. The detector becomes more sensitive to spatial resolution limitations such as diffusion once a lower drift velocity is available.

The time-difference measurements were found to be limited by signal-to-noise effects. Evidence for this came from the fact that the resolution improved with gas gain. In addition, the discrimination studies provided further evidence that noise was limiting the measurement. Use of a shorter constant fraction delay time, which is more sensitive to noise, provided a poorer time-difference measurement. The sensitivity of this measurement to the contribution of small distortions of the signal was made evident by the presence of a z dependent crosstalk phenomenon. It has been shown that z measurements using time-difference require correct termination of all electrodes in the chamber and minimal noise. Under optimal conditions the time-difference resolution was measured to be 100 ps . This was for the 'near' wires in argon-ethane(50-50) at the highest gas gain and is equivalent to a spatial resolution of 2 cm .

The second hit efficiency of the detector is 0.5 when the second hit is 2 mm from the first hit. This is a consequence of the inability of the discriminator to re-fire on a second pulse if it is superimposed on the tail of a earlier pulse. As expected, the resolution of the second pulse was degraded as the two pulses arrive closer in time.

An evaluation of the absolute drift time resolution was provided by measuring the z resolution using the combined axial and stereo cell data. This revealed that the chamber geometric and electronic calibrations did not contribute significantly to the resolution. In the cool gas, however, residual systematics in the time-to-distance relation contributed between 20 and $25\text{ }\mu\text{m}$ to the resolution. Given the cool gas resolutions, a z impact parameter as low as $240\text{ }\mu\text{m}$ can be expected with this detector operating with the OPAL Jet and Z chambers for high momentum tracks.

Chapter 5

Detector Systematics and Calibration Procedures

Maintaining a high intrinsic resolution in the measurement of the absolute space point of an ionizing interaction requires knowledge of the detector systematics. These include the geometric and electronic constants of the detector as well as the dependencies of the time-to-distance relationship on a variety of physical quantities. These systematics are discussed in this chapter and some calibration methods that account for them are presented.

The calibration of the detector when operated with CO₂-isobutane(80-20) gas was considered because of the excellent intrinsic resolution it exhibited in the detector. Moreover, because its velocity is linearly dependent on the electric field, experimentation with this gas provided a useful laboratory for evaluating the electrostatic calculations and the ability to use such calculations in determining time-to-distance relations. Such an examination can provide insights into the systematics of the time-to-distance relations of other gases used in a minijet chamber including those that have time-to-distance relations that are less sensitive to the electrostatic fields.

In cell-based drift chambers, unlike jet chambers, the time-to-distance relation can be calibrated by examining systematic deviations of hits from a track using the uncorrelated drift time measurements. Often a completely arbitrary function

such as a cubic spline is used to describe the relation. In a simple jet chamber, such as the OPAL vertex detector, this technique fails because most tracks traverse a single jet cell in which all drift time measurements are highly correlated. Some external constraints must be imposed to calibrate the time-to-distance relation¹. Use of external constraints in the calibration is optimized if a physical model of the detector is incorporated into the time-to-distance relation. Whether or not such a model can be used depends on how accurately the electrostatic fields (and a variety of other physical constants) are known. The jet chamber geometry lends itself to reliable electrostatic field calculations because of the ability to position and survey wires with a precision at a level comparable to the intrinsic resolutions of the detector. Therefore there is potential for using a physically motivated time-to-distance relation in this detector.

It will be demonstrated in this chapter that the time-to-distance relation in the prototype minijet chamber can be described quantitatively with a very small number of free parameters that are associated with physical characteristics of the chamber. In particular, the velocity dependence on electric field was described in terms of three free parameters that were subsequently used with a calculation of an electrostatic field map to generate the time-to-distance relation.

The goal was to examine whether or not it was possible to describe the properties of the detector with sufficient accuracy to use such a technique in the calibration procedure. The two central axial cells in the prototype were used for this study². A small set of 'monitor parameters' was chosen to evaluate the absolute precision of the two cells while systematically varying a number of quantities. In this way important physical effects that would have to be taken into consideration in constructing a more complete model were revealed.

¹In the OPAL Jet chamber, for example, a set of laser beams illuminating the detector provides such constraints.

²The test beam was directed mainly through those cells. The stereo cells were not considered because of the smaller number of measurements available in them.

5.1 Calibration Basics

The following information is required to convert a drift time measurement to an absolute position in the r - ϕ plane of the detector:

- the sense wire position in the r - ϕ plane: $(X0, Y0)$.
- the time corresponding to ionization from a track that passes through the sense wire: $T0$.
- the direction of the electron drift.
- the function that converts the drift time to the drift distance: $D(t-T0)$.

In this section the use of these quantities in the drift time to space point conversion will be introduced. Although the goal of the work presented in this chapter was to investigate whether or not $D(t-T0)$ for CO_2 -isobutane(80-20) can be described using a physical model of the detector, it was first necessary to calibrate the geometric and electronic calibration constants. In Sections 5.2 to 5.3 the calibration approach used in the prototype studies will be discussed. This section is meant to provide an introduction of the various parameters that can influence the calibration.

5.1.1 The time-to-distance relation: $D(t-T0)$

In general, the arrival time of a cluster of electrons drifting between x and $X0$ is,

$$t - T0 = \int_{X0}^x \frac{dx}{v_d(x)} \quad (5.1)$$

The time-to-distance relation, $D(t-T0)$, is essentially the inverse of the function of x in Equation 5.1. For the simple case in which the electron drift velocity, v_d , is uniform throughout the drift region and all electrons contributing to the timing signal arrive at the sense wire at the same time,

$$D(t - T0) = v_d \cdot (t - T0).$$

In the OPAL vertex detector the velocity is *not* uniform throughout the drift region and all electrons do *not* arrive at the sense wire at the same time. The systematic dependencies of a non-uniform drift velocity and non-isochronous electron arrival time must be understood if the intrinsic resolution is to be preserved in an absolute spatial measurement. The resolution measurements presented in Chapter 4 indicated that an intrinsic resolution of $25\ \mu m$ can be achieved in the 2.5 bar CO₂-isobutane data when averaged over the drift space beyond the first millimetre of drift. Diffusion made the resolution a drift distance dependent quantity so that at a distance of 10 mm from the wire the resolution was $29\ \mu m$. This implies that the drift distance can potentially be measured to $\pm 0.3\%$ thus setting the scale for how well $D(t-T_0)$ must be known.

5.1.2 Gas related systematics of $D(t-T_0)$

The drift velocity depends on the gas composition, density and temperature as well as on the electrostatic field in the detector.

The CO₂-isobutane gas mixture used throughout the prototype studies was assumed to be constant within the uncertainties of the mixing procedure. The drift velocity dependence on relative concentrations of CO₂ and isobutane has been studied by Becker et al. [57]. The Becker studies suggest that for the drift fields used in the prototype for the CO₂-isobutane(80-20) experiments the drift velocity increases by 1% for each percent increase in the proportion of isobutane. As described in Chapter 3 the gas pressure was measured to $\pm 5\ mbar$ and the mixing of the CO₂-isobutane gas was performed using partial pressures. Therefore, the proportion of isobutane in the 2.5 bar mixture was $20.0 \pm 0.2\%$. Using the Becker results, an uncertainty of 0.2% in the proportion of isobutane meant that changes in the drift velocity associated with a slightly different gas composition from one gas fill to another may have occurred at the 0.2% level during the experiments with the

prototype.

In Chapter 4 it was demonstrated that the gas gain was constant throughout the data taking period and that at the end of a gas fill there was no evidence for loss of electrons as a function of drift time. This provided evidence that contaminants in the gas with an affinity for electrons (such as oxygen) were not present in sufficient quantity to significantly alter the detection efficiency of the chamber.

The dependency of v_d on gas density, ρ , and temperature, T , near the ambient temperature of $T_a = 294\text{ K}$ scale as 58]

$$v_d = \begin{cases} \frac{T}{T_a} f\left(\frac{E}{P}\right) & \text{for } \frac{E}{P} \lesssim 1000\text{ kV/cm} \\ g\left(\frac{E}{\rho}\right) & \text{for } \frac{E}{P} \gtrsim 1000\text{ kV/cm} \end{cases} \quad (5.2)$$

If $f\left(\frac{E}{P}\right)$ is a linear function, as is approximately the case with CO_2 -isobutane, then v_d only depends on ρ . In Section 4.1.3 it was demonstrated that the gas density was constant to better than the measurement error of $\pm 0.15\%$. Therefore, any instability in $D(t-T_0)$ caused by changes in the gas density was less than $\pm 0.15\%$ during the prototype studies.

A more subtle gas related systematic is the dependence of T_0 on the drift velocity of the gas. The T_0 is defined in this study as the time between the TDC start signal and a stop signal produced by an ionizing track that passes through the wire. Various physical contributions to the T_0 can be identified. In particular, not only do the propagation times in the cables and electronics contribute to the T_0 but also the time associated with the collection of a sufficient number of electrons drifting in the gas. In Appendix D a complete description of the method of obtaining T_0 s is described. Briefly, the method used the front edge of the TDC distribution with the front edge defined as the point at which the cumulative (i.e. integral) TDC distribution intersects the time axis. Because of the dependence of electron collection time on the drift velocity the T_0 may be expected to depend on the drift velocity in the vicinity of the anode. This was in fact observed when the T_0 's

for argon-ethane(50-50) and CO₂-isobutane(80-20) were determined using the same cable and electronics configuration: a T0 difference of $2.2 \pm 0.4 \text{ ns}$ was measured. The difference in T0s when the cool gas pressure was changed from 2.0 to 2.5 bar was less than the measurement error. The drift field for both pressures was 3.2 kV/cm while the anode surface fields were 520 and 600 kV/cm respectively. This information was used to ensure that the T0 was calibrated for each gas separately. It also demonstrated that T0 is relatively insensitive to changes in pressure for the electric fields used in the prototype.

5.1.3 Isochrone effects

In a jet cell the direction of the electron drift is perpendicular to the anode plane over most of the drift space with the sign of the drift direction determined by the anode wire offsets or staggers. The resolution of the left-right ambiguity is handled on a track-by-track basis. However, in the region close to the anode wire the direction changes as the electrons drift directly towards the wire. A plot of the isochrones (i.e. curves of equal electron arrival time in the $r-\phi$ plane) of two central sense wires in the prototype operating with CO₂-isobutane along with a plot of the electron drift paths overlayed on the isochrones are presented in Figure 5.1. The isochrones are U-shaped with the bottom of the 'U' forming the arc of a circle. At increasing distance from the sense wire the radius of the isochrone also increases up to some maximum value, referred to here as ' R_{iso} ', beyond which the isochrone radius is constant. From Figure 5.1 it can be seen that it is at a distance of 2 to 3 mm from the wire that the electrons change direction from motion that is perpendicular to the anode plane to motion that is directed radially towards each wire. Because of these circular isochrones the arrival time of the earliest electron clusters depend on the angle of the track relative to anode plane: ϕ . It is therefore useful to combine the drift direction and $D(t-T_0)$ into a single function: $D(t-T_0;\phi)$. $D(t-T_0)$ is the distance drifted by the electrons that arrive at the wire first. $D(t-T_0;\phi)$ is defined

Figure 5.1: (a) Isochrones in the prototype with 2.5 bar CO_2 -isobutane(80-20) with a drift field of 3.2 kV/cm and anode surface of 540 kV/cm (b) electron drift paths overlaid on the isochrones of (a).

Figure 5.2: Definition of $D(t-T0;side;\phi)$ in the calibration used for the vertex prototype studies of detector systematics

as the distance between the sense wire and the point on the track that lies along the line running perpendicular to the anode plane as shown in Figure 5.2. From simple geometry, the conversion from $D(t-T0)$ to $D(t-T0;\phi)$ associated with the change in direction of the first electrons as they enter the anode region is:

$$D(t - T0; \phi) = \begin{cases} D(t - T0) \sec \phi & D(t - T0) \leq R_{100} \\ D(t - T0) + R_{100}(\sec \phi - 1) & D(t - T0) > R_{100} \end{cases} \quad (5.3)$$

It is apparent from Figure 5.1 that the value of R_{100} depends on whether the ionization comes from the 'near' or 'far' side of the wire (the upper wire is a 'far' wire and the lower wire is a 'near' wire in the figure). Therefore a different R_{100} is needed for 'near' and 'far' sides. Failure to include this difference was evident in the data as a ϕ dependence of the deviation between the 'near' and 'far' wire track

Figure 5.3: Magnitude of the electric field as a function of D for both the 'near' and 'far' sides of a wire in the prototype. The drift field is 3.2 kV/cm and the anode surface field is 540 kV/cm . D is defined in Figure 5.2.

residuals ($RSDL^{near} - RSDL^{far}$):

$$RSDL^{near} - RSDL^{far} = (R_{iso}^{near} - R_{iso}^{far})(\sec \phi - 1)$$

5.1.4 'Near' and 'Far' electric field differences

From Figure 5.1 it can be seen that the drift paths (and hence electric field) are different for the upper wire displayed, which is a 'far' wire, compared to the lower wire which is a 'near' wire. The magnitude of the electric field as a function of D is presented in Figure 5.3 with the 'near' and 'far' sides overlayed. Since the

drift velocity depends on the field and $D(t-T0;\phi)$ depends on the drift velocity, the time-to-distance relation also depends on whether the track is on the 'near' or 'far' side of an anode wire: $D(t-T0;\phi;side)$.

5.1.5 Z dependencies

Also important is the significant dependence of the calibration on the z coordinate of the hit. This dependency arises in two ways. The first is associated with the gravitational and electrostatic deflections of the anode wires. This introduces a z dependence to $X0$. The second is a consequence of the fact that the wires were deflected. A large displacement of the wires at the centre of the chamber introduced important perturbations to the electrostatic fields just as in the case of the 'near-far' field differences. In this case the field changed continually with z thereby resulting in a z dependent time-to-distance relation: $D(t-T0;\phi;side;z)$.

5.1.6 Summary of the calibration basics

Knowing the wire position, $T0$, z , ϕ and $D(t-T0;\phi;side;z)$ the position of ionization detected on an anode wire ' $iwire$ ' in the local coordinates of a jet cell³ is:

$$\begin{pmatrix} x_{iwire} \\ y_{iwire} \\ z_{iwire} \end{pmatrix} = \begin{pmatrix} RX0_{iwire}(z) - D((t - T0);\phi;side;z) \\ Y0_{iwire}(z) \\ Z(\Delta t_{end})_{iwire} \end{pmatrix} \quad (5.4)$$

$RX0$ is used to denote the x -coordinate of a wire relative to the other wires in the same jet cell: it is the x -coordinate of the wire in the local coordinate system. The calibration task essentially involves the determination of the wire position, $T0$, and $D(t-T0;\phi;side;z)$ for the detector. During the prototype tests the z position of the beam was known and was used in the analysis to set the z values for calculating $RX0(z)$ and $D((t-T0);\phi;side;z)$. In the vertex detector at LEP it will be necessary

³In the local coordinate system of a jet cell the y -axis is defined by the guard wire plane and the local coordinate origin is coincident with the OPAL coordinate system origin.

to use the time-difference information to obtain the z value for each hit. This is discussed in Section 5.5.

The problem of not knowing the ϕ of a track was treated iteratively during the analysis of the prototype data. A track was fit assuming $\phi=0$ so that $D(t-T_0; \phi=0; \text{side}; z)$ was initially used to convert the drift time to a distance. The local ϕ of the track obtained from the fit was then used to recalculate the drift distances from the drift times using $D(t-T_0; \phi_{\text{track}}; \text{side}; z)$.

5.2 Calibration of Geometric Constants and an Evaluation of the Electrostatic Field Calculations

The determination of the wire positions are discussed in this section. In the case of the OPAL vertex prototype RX0 depends sensitively on the gravitational and electrostatic deflections of the wires. As a consequence, the calibration of RX0 can be used to evaluate the reliability of the electrostatic calculations. The wire tensions were measured and various components of the detector were surveyed while the prototype was being constructed. This information provided the necessary input for a calculation of the wire deflections. The level of agreement between the calculation and measurements was used to assess the validity of the electric field calculations and also provided an evaluation of the systematic uncertainties of the calibration of geometric constants.

$Y_{0, \text{wire}}$ is essentially the radial coordinate of *wire* in the OPAL coordinate system. The vertex measurement is relatively insensitive to this constant because an error δY_0 in Y_0 is equivalent to a drift distance measurement error of $(\delta Y_0 \cdot \tan \phi)$. Since at LEP most tracks will have $\phi < 5^\circ$ in this detector a value of δY_0 equal to $100 \mu\text{m}$, for example, corresponds to an equivalent systematic drift distance error of less than $9 \mu\text{m}$. The Y_0 wire positions in the prototype were surveyed at con-

struction time with an uncertainty of better than $\pm 20 \mu m$ which implies that such a survey is sufficiently accurate to provide the Y_0 values for the wires in the detector. The z dependence of Y_0 is relatively small and is associated mainly with gravitational sag and small electrostatic deflections. Such corrections were not included in the calibration of the prototype detector.

The uncertainty in X_{wire} is a systematic error that contributes directly to the measurement of the impact parameter and therefore must be made considerably smaller than the detector's intrinsic drift distance resolution. Wire locations in the detector are determined by the placement combs described in Chapter 3. Use of these combs introduced a natural separation of the calibration of wire positions into two components:

- the position of an individual sense wire relative to the guard plane on the same comb⁴: RX_0
- the relative position and orientation of one sense wire plane relative to another: $GLOX_0$ and Φ_{anode}

The combs and comb-positioning dowel holes on the chamber end plates were surveyed at the time of the construction of the prototype and the wire tensions were measured. A complete prediction of the position of the sense wires required the use of a calculation of the wire deflections based on the electrostatic fields in the chamber using the surveyed wire positions and wire tension measurements as input. The results of such calculations are presented in Section 5.2.3.

An independent calibration of wire positions using tracks at a variety of orientations and with different fields in the chamber provided an experimental investigation of the systematics of the determination of the wire positions. In addition, this cal-

⁴The guard plane lies between the two planes of staggered anodes and thereby defines the y -axis in the local coordinate system of a single jet cell.

ibration was used to examine the value of wire placement predictions based on the electrostatic deflection calculations.

5.2.1 Calibrating RX0 using track residuals

Calibration of $RX0(z)$ can be performed in a jet chamber provided the time-to-distance relation is known. The relative positions are obtained from systematic deviations of hits from the fitted tracks. Initially it is assumed that the wires are at their nominal deflected positions. A line is fit to each track and the residuals of the fit are accumulated in separate histograms for each wire. The mean of the residual distribution of each wire is then used to directly correct the value of $RX0(z)$. It is assumed in this procedure that the tracks are fitted in real space and therefore a reasonable time-to-distance relation must be available for this approach to work. Also, $RX0$ starting values must be provided that are within several hundred microns of the true $RX0$. Finally, because $RX0(z)$ is a function of z the value of z must be known for each track. For the test beam experiments with the prototype the beam was set at a various values of z and $RX0(z)$ was calibrated as a function of z knowing the z position of the beam. The central value of the z of the beam was known to within ± 0.3 cm and the beam width was several centimetres in z . This information was sufficient for determining $RX0(z)$ ⁵.

The cool gas time-to-distance relation is strongly dependent on the electric field and the field depends on the wire positions. Therefore the initial calibration of wire positions relied on the argon-ethane(50-50). Because this gas has a saturated drift velocity in the uniform electric field region of the drift cell the time-to-distance relation is simply:

$$D(t - T0) = v_d \cdot (t - T0).$$

⁵In a non-test beam environment the time-difference measurement and stereo cell provide the z information required for the $RX0(z)$ calibration.

To conduct a wire position calibration it was therefore necessary to calibrate the argon-ethane T0 values for each wire and the value of v_d in the uniform field region. The T0s were calibrated to within $\pm 0.2 ns$ using the method described in Appendix D. The velocity was measured by scanning the test beam in ϕ while illuminating the chamber with particle tracks. This method of determining the velocity is based on the fact that the slope of a track as measured using the drift times of the wires positioned along the y-axis is proportional to the drift velocity:

$$\frac{dx}{dy} = v_d \frac{dt}{dy}$$

First it was assumed that each wire has the same drift velocity, v_a . The initial value of the velocity for the 3.75 bar argon-ethane(50-50) data for a drift field of 3.2 kV/cm was assumed to be $53 \mu m/ns$. Beam tracks were fitted in the uniform field region only. The mean track slope relative to the anode plane was determined in each jet cell for each ϕ position. The calibrated drift velocity, v_d , was extracted by fitting for v_a , v_d in:

$$slope = \frac{v_a}{v_d} \tan(\phi + \phi_0)$$

In the test beam a ϕ scan was made with the argon-ethane(50-50) gas at 3.75 bar and was used to measure the drift velocity to $\pm 1\%$. The dominant error was associated with the uncertainty in the ϕ setting of the test beam. The data from that scan is presented in Figure 5.4. The velocity for the drift field of 3.2 kV/cm was measured in this way to be $52.34 \pm 0.52 \mu m/ns$.

To ensure that the wires were in a reasonable position before conducting a wire-by-wire calibration, the mean distance between the odd and even numbered wires was first calibrated. This provides a determination of the large effects of the anode wire offsets (i.e. staggers) before turning to the individual wire positions. This was accomplished by fitting a line to the tracks which had one slope but a different intercept for the odd and even numbered wires. In this three parameter linear fit the difference between the odd and even intercepts is zero when the wire positions

Figure 5.4: $\langle \phi_{\text{measured}} \rangle$ vs $\phi_{\text{test-beam}}$ for one of the jet cells in the prototype

are properly calibrated. At the centre of the chamber, where the electrostatic bow produced a maximum odd-even stagger of the wires, the distance between the planes was nearly 1 mm for a drift field of 3.2 kV/cm. Since the drift velocity was measured to $\pm 1\%$ the spacing between odd and even wire planes within a single jet cell were measured with an absolute precision of $\pm 10 \mu\text{m}$ in this way.

Having obtained reasonable odd-even relative wire plane locations the individual RX0(z) wire positions within the plane were calibrated using mean track residuals. In the process of extracting the residuals it was essential to remove any slope in a linear fit to the *Wire No. vs <Residual>*. This is because such a slope is completely spurious since there is no information about systematic shifts in the orientation of the sense wire plane in the tracking information. Such spurious slopes arise from statistical fluctuations and failure to remove them would result in the introduction of a false orientation of the plane.

5.2.2 The Z dependence of RX0: the bowing function

The z dependence of RX0(z) associated with the electrostatic deflections in the detector was described by:

$$RX0(z) = RX0(z=0) \cdot \cos \left(\frac{z}{z_{end}} \cos^{-1} \left(\frac{RX0(z=z_{end})}{RX0(z=0)} \right) \right) \quad (5.5)$$

This function is based on the fact that in this chamber geometry the x component of the electrostatic force, F_x , is proportional to RX0:

$$\frac{F_x}{T} = f \cdot RX0$$

and the assumption that the deflection is small compared to the length of the wire. T is the tension and f is the proportionality constant. The value of f, expressed in terms of the wire position at the centre and ends of the detector, is:

$$f = \left(\frac{1}{z_{end}} \cos^{-1} \left(\frac{RX0(z=z_{end})}{RX0(z=0)} \right) \right)^2$$

For the values of $RX0(z=0)$, $RX0(z=z_{end})$ and z_{end} in the prototype detector when it was operated with a drift field of 3.2 kV/cm an expansion of the cosine function with terms up to z^4 could be used.

$$RX0(z) = RX0(z=0) \cdot \left(1 - \frac{fz^2}{2} + \frac{f^2z^4}{24}\right)$$

This expansion of the function was used in the analysis calibration code for the prototype.

The only parameters required for the function in Equation 5.5 were z_{end} , $RX0(z=0)$ and $RX0(z=z_{end})$. z_{end} was set equal to the z position of the wire positioning combs: 52.5 cm . $RX0(z=0)$ was measured using tracks at the centre of the detector: $RX0(z=0)_{track}$. $RX0(z=z_{end})$ was obtained using the nominal positions of the wire positions on the combs together with the $RX0(z=0)_{track}$. The calibrated positions of the wires on the combs were obtained from the $RX0(z=0)_{track}$ measurements and an electrostatic calculation of the deflected wire positions: $RX0(z=0)_{calc}$ ⁶. The nominal values of $RX0(z=z_{end})$ were used as input to the calculations.

$$RX0(z=z_{end}) = RX0(z=z_{end})_{nominal} \cdot \frac{RX0(z=0)_{track}}{RX0(z=0)_{calc}} \quad (5.6)$$

This technique of scaling $RX0(z=0)_{track}$ to obtain $RX0(z=z_{end})$ was tested by comparing values of $RX0(z=z_{end})$ obtained using the scaling to the values obtained from the survey of the grooves in the combs⁷. The RMS deviation between surveyed values and the values obtained using the tracks at $z=0$ scaled to $z=z_{end}$ was less than $8 \mu\text{m}$. The error is dominated by the precision of the survey measurements. The tracking technique was the preferred method because, as described above, the error on the measurement at $z=0$ is $\pm 10 \mu\text{m}$ which meant that the error on $RX0(z=z_{end})$ was $\pm 3 \mu\text{m}$.

Another test of this technique was obtained by measuring $RX0(z)$ at 7 values of z by scanning the test beam in z . The $RX0(z=0)$ and $RX0(z=z_{end})$ were obtained by

⁶The deflection calculation method is described in Reference 59.

⁷The groove positions from opposite ends of the wire were averaged

fitting the function in Equation 5.5 to the 7 points in z . Figure 5.5 is a sample of plots of the data and fitted functions in one of the axial cells. The RMS deviation between the data and fit was $5.2 \pm 1.7 \mu m$. When only $RX0(z=0)$ was used to specify both parameters of the function using Equation 5.6 the RMS deviation was $6.9 \pm 1.8 \mu m$. This demonstrated that a measurement of $RX0(z=0)$ is entirely satisfactory to describe $RX0(z)$ for all other values of z when used with the bowing function of Equation 5.5.

A final question that has been addressed is whether or not a simple quadratic would suffice as a bowing function. The quadratic which is constrained at $RX0(z=0)$ and $RX0(z=z_{end})$ was considered:

$$RX0(z) = RX0(z=0) - [RX0(z=0) - RX0(z=z_{end})] \frac{z^2}{z_{end}^2}$$

The z -scan data was used to examine this question. When only $RX0(z=0)_{track}$ was used to specify both parameters of this function the RMS deviation of $RX0(z)$ data from the quadratic function was $7.7 \pm 2.4 \mu m$. There are systematic trends that contribute to a degradation in the wire positioning error but a comparison of the 7.7 to $6.9 \mu m$ RMS deviations in this analysis demonstrates that in practice they do not dominate the wire positioning uncertainty. Note that this quadratic form is *not* a truncation of the expansion of Equation 5.5. It provides reasonable agreement with the data because the maximum deviation of the quadratic from the full bowing function is small over most of z . The deviation is less than $15 \mu m$ over the entire length of the wire and is greater than $10 \mu m$ over only 20% of the wire's length.

5.2.3 Evaluating the wire deflection calculations

The calculations of the electric field required the input of anode positions relative to each other on the combs, the small anomalous mechanical rotations and offsets of the anode and cathode planes in the prototype and the wire tensions. Because $RX0(z)$ is a sensitive function of the drift field (see Figure 4.8) a comparison of the

Figure 5.5: RX0 vs Z an axial cell. The RX0 data points have a 1% systematic uncertainty that amounts to $\pm 5 \mu m$ at $z=0$. The curves are fits to the data using the function in Equation 5.5.

measured $RX0(z=0)$ values with the values predicted by the deflection calculation provided a means of evaluating the reliability of the electric field calculations.

A reliable calculation depended on the details of the detector geometry. Wire positions on the combs and systematic rotations and offsets of the anode and cathode planes on the combs were measured relative to the comb dowel holes using a *Mitutoyo* Profile Projector model PJ-300⁸ which had a $\pm 10\mu m$ precision. The dowel holes in the G-10 end plate were measured to a precision of $\pm 8\mu m$ using a *Bentix* Coordinate Measuring Machine⁹. If the systematic uncertainties of the surveys are added linearly the uncertainty in relative positions of the anode and cathode planes is $18\mu m$. For a 1 cm drift gap this could account for a drift field uncertainty of approximately $\pm 0.2\%$. The calculation is only treated in two dimensions and is used to compare measurements of the sagitta of the wire bow, that is, $RX0(z=0)$. Therefore, the average of the rotations and offsets of the combs on both ends were used in the calculation.

The $RX0(z=z_{end})$ values were determined using the calibration technique of Equation 5.6. Only the positions of individual wires *relative to each other on the end plate* were measured in this way. Because $RX0(z)_{track}$ is not sensitive to global rotations or offsets of the jet cell these effects were removed from the data before making a final comparison with the calculations. The comparison between the measurements and electrostatic calculations are presented in Table 5.1 for the two central axial cells.

The difference between the measured and calculated sagitta of the sense wires averaged over all values in Table 5.1 is $2.4 \pm 1.5\mu m$. The RMS deviation from this mean difference is $9.0 \pm 1.0\mu m$. The RMS value is used to represent the uncertainty in the position obtained from the electrostatic deflection calculation for any given wire. It is consistent with the uncertainty in the position of the wire at $z=z_{end}$:

⁸Measured at the Science Technology Centre at Carleton University.

⁹Measured at Westinghouse Canada Inc., Renfrew Ont.

Axial Wire	$E_{drift} = 3.0 \text{ kV/cm}$ $E_{anode} = 475 \text{ kV/cm}$			$E_{drift} = 3.2 \text{ kV/cm}$ $E_{anode} = 500 \text{ kV/cm}$			$E_{drift} = 3.2 \text{ kV/cm}$ $E_{anode} = 540 \text{ kV/cm}$		
	meas. μm	calc. μm	meas.-calc. μm	meas. μm	calc. μm	meas.-calc. μm	meas. μm	calc. μm	meas.-calc. μm
1	507	515	-7.8	511	511	0.1	510	511	-0.6
2	490	493	-3.3	470	467	3.9	487	494	-7.0
3	525	514	10.5	532	530	2.3	527	525	1.6
4	475	469	6.3	447	452	-4.5	474	475	-1.2
5	487	506	-19.0	520	520	-0.3	509	513	-4.2
6	487	471	16.	466	459	7.0	487	479	7.6
7	519	499	20.2	534	531	3.2	519	521	-2.0
8	454	447	6.7	430	434	-4.4	454	452	2.4
9	494	487	7.5	510	507	2.6	493	496	2.8
10	453	467	-13.7	446	443	3.1	455	460	-4.8
11	532	526	6.0	549	544	5.1	536	532	4.4
12	394	361	33	389	381	7.7	397	398	-1.0
Mean			5.2 ± 4.2			2.2 ± 1.1			-0.17 ± 1.2
RMS			14.6 ± 3.0			3.9 ± 0.8			4.1 ± 0.8

Table 5.1: Calculated and measured anode positions at $z=0$ using tracks in argon-ethane (50-50). The unsigned distance between the wire position at $z=0$ and the nominal guard plane is listed.

an error in $RX0(z=z_{end})$ of $3 \mu\text{m}$ increases by a factor of three to $9 \mu\text{m}$ at $z=0$ because of the scaling of Equation 5.6. The average difference between measured and calculated wire positions is less than two standard deviations away from zero which implies consistency within the measurement uncertainties.

If it is assumed, however, that the mean difference is entirely associated with the uncertainty in the drift field then it can be used to evaluate how well the drift field is known. The $2.4 \mu\text{m}$ uncertainty can be converted to an equivalent global drift field error using the parameterization of $RX0$ as a function of drift field given in Equation 4.1. This produces an equivalent error in the 3.2 kV/cm global drift field of 0.0039 kV/cm or $\pm 0.12\%$. Such an uncertainty can be entirely accounted for by the errors in the positioning of the anode and cathode planes. An uncertainty in the field at this level is acceptable for operating the detector with a cool gas.

5.2.4 Position and orientation of the anode-guard plane

Just as with the relative positions of individual wires in a single sense wire plane, the plane itself cannot be assumed to be at its nominal position nor can the angle between one jet cell and other be assumed to be exactly 10° . In this detector a shift or rotation of the sense wire plane from nominal can be introduced in at least the following three ways:

- They can be affected by a shift or rotation of the comb that defines the sense wire locations. This can come about if one or both of the dowel holes used to locate the comb on the end plate is different from its nominal location.
- The line of wire positioning grooves on the comb may be systematically shifted or rotated on the comb.
- The plane of sense wires can be rotated and shifted because of electrostatic deflections of individual wires that systematically vary with the Y0 coordinate of the wire¹⁰.

Because of small asymmetries at the two end plates and the fact the electrostatic induced rotations are a maximum at the centre of the chamber these rotations and shifts are z-dependent.

A feature of the jet cell geometry is that the calibration of these global geometrical shifts and rotations cannot be determined using tracks within a single jet cell. A sufficient number of external constraints is required to handle all possible degrees of freedom. The tracking data obtained with the prototype did not have enough appropriate constraints with sufficient precision to enable a calibration of the absolute geometry of the detector to be performed at the same level of precision as the RX0 measurements. As a result, surveys of the combs and end plate

¹⁰This effect occurs even when the fields are at their nominal value. For the electrostatic fields used in the prototype the electrostatic induced plane rotation was calculated to be as high as 0.1° .

dowel holes have been used to calibrate the mechanical rotations and offsets. Deflection calculations have been used to correct the electrostatic induced rotations. These surveys demonstrated that the positions of the wires were symmetric with respect to either end of the chamber within the error of the total survey measurement ($\pm 15 \mu m$). The surveyed value for the angle between the two central jet cells, Φ_{anode} , was $9.933 \pm 0.034^\circ$. The value for the offset in the x direction of the origins of the local coordinate systems of the two cells, GLOX0, was $178 \pm 66 \mu m$ ¹¹.

The only independent check on this survey information was provided by the ϕ scan data described in Section 5.2.1. Determination of v_d using the scan in ϕ as described in Section 5.2.1 provided a 1% measurement of v_d in each of the adjacent cells. Once the velocities were known the measurement of the slope of the tracks measured relative to one anode plane as compared to that measured by an adjacent plane provided a measure of the angle between the two planes, Φ_{anode} . Such a measurement was performed with the ϕ -scan data from the test beam and a value of $9.94 \pm .08^\circ$ was obtained. The large error is a consequence of the uncertainty in the velocity originating in the ϕ setting errors. Within the measurement errors this is consistent with the surveyed value and is therefore useful in ruling out any large errors in the survey.

5.2.5 Summary of geometry calibration

It was demonstrated in this section that the wire positions relative to each other within a jet cell were determined with an uncertainty of $\pm 9 \mu m$, the relative position of origin of the local coordinates system of the two adjacent cells was known to $\pm 66 \mu m$ and the angle between the two adjacent planes of sense wires had an uncertainty of $\pm 0.034^\circ$. The relative wire positioning error is based on the deviation

¹¹The large error on GLOX0 is produced by the lever arm between the centre of the detector where the origins are located, and the dowel holes which determine the position and orientation of the combs.

between the predicted positions of the wires using a calculation of electrostatic deflections and measurements for several operating conditions and track orientations. The relative position and orientation of the adjacent cells were determined using information from the survey of the detector.

The z -dependence of the wire positions was handled through the use of a 'bowing function' that provided the wire position as a function of z with an error of $\pm 5 \mu m$. In the prototype only two parameters were required to describe this function: $RX0(z=0)$ and $RX0(z=z_{end})$. The geometrical rotations and offsets were applied directly to the $RX0(z=z_{end})$ values. These were then used as the input to an electrostatic deflection calculation. Because the combs were used to locate both the anode-guard planes and cathode planes, the surveyed position and orientation of the combs were included in defining the cathode wire locations for the deflection calculation. The final deflected locations as calculated with the electrostatics were used to adjust the $RX0(z=0)$ values. The z dependence of this is accounted for in the bowing function.

Having obtained a calibration of the geometry of the detector the goal of developing a cool gas time-to-distance relationship was undertaken. The merit of the geometry calibration lay not only in the determination of the wire positions but also in the demonstration that the electric fields were well enough understood to correctly predict a measureable quantity that depended in a sensitive way on the fields. This provided confidence that a time-to-distance relation based on electrostatic field calculations could be developed for this detector.

5.3 $D(t-T_0)$ of a Cool Gas

The intrinsic resolution of the detector was improved by more than a factor of two by using a gas with a velocity that is roughly proportional to the drift field and by operating at a relatively low drift field. The consequence of this is that the absolute

resolution is now significantly influenced by the systematics associated with four physical quantities: the field, pressure, temperature and precise gas composition. If the physics of the detector is fully understood then the absolute resolution is optimized by using a time-to-distance relation that can directly incorporate known changes in the four quantities.

In principle, changes in these quantities can be monitored and appropriate corrections to the time-to-distance relation can be made. To accomplish this a time-to-distance relation that is based on the physics of the detector was developed. Not only is this useful for optimizing the calibration but it also facilitated the study of the detector's systematics in the first place. The details of the cool gas time-to-distance relation that was developed to examine the systematics in the prototype are presented in this section.

5.3.1 Velocity vs electric field parameters

If the assumption is made that the electric field can be reliably calculated in a jet chamber geometry then the time-to-distance parameterization in a given gas at fixed temperature and pressure depends solely on the electric field dependence of the drift velocity. The current published data on this dependence demonstrate that there is little deviation from

$$v \propto \frac{E}{P}$$

up to E/P values of 2 kV/cm bar in CO_2 -isobutane (80-20) 55 .

Although the detector operates within this linear range over most of the drift gap, in the region within 1 mm of the anode wire there is little detailed knowledge about the field dependence of the velocity. Calculations of the drift velocity based on electron transport theory indicate that the velocity saturates at some value of the electric field [46]. The solid curve in Figure 3.4 indicates that this occurs at fields of approximately 10 kV/cm bar .

To accommodate this saturation two additional parameters, k_2 and k_3 , were introduced. k_2 was introduced to provide a first order deviation from a linear dependency while k_3 was used to smoothly saturate the velocity to v_{sat} at the saturation field, E_{sat} where

$$\left. \frac{dv}{dE} \right|_{E_{sat}} = 0.$$

The velocity-field dependence is then given by:

$$v_d = \begin{cases} k_1 E (1 - k_2 E + k_3 E^2) & E < E_{sat} \\ v_{sat} = k_1 E_{sat} (1 - k_2 E_{sat} + k_3 E_{sat}^2) & E > E_{sat} \end{cases} \quad (5.7)$$

This is plotted in Figure 5.6 using values for k_2 and k_3 that were used in the calibration of the prototype detector.

To further emphasize the physical significance of this treatment, the parameters VEL and E_{sat} were defined for external reference purposes while maintaining k_1 and k_3 as dependent internal parameters. The relations between these are:

$$k_3 = \frac{-(1 + 2k_2 E_{sat})}{3E_{sat}^2}$$

$$k_1 = \frac{VEL}{E_d(1 - k_2 E_d - k_3 E_d^2)}$$

where E_d is an arbitrary field at which VEL is defined. During these studies E_d was chosen to be $3.2kV/cm$ since this was the nominal drift field for most of the data. VEL is equal to the drift velocity of the time-to-distance relation only where the field is exactly $3.2kV/cm$. It can also be used to estimate the slope of the v vs E dependence for small fields.

The parameters k_1 , k_2 and k_3 together with the electric field were then used to determine the time-to-distance relation. The time-to-distance relation was calculated by initially assuming that the timing signal is associated with the arrival of an electron cluster produced along the field line perpendicular to the anode plane that passes through the anode wire. The field along this line is a function of the

Figure 5.6: Velocity vs Electric Field Using k_1, k_2 and k_3

Resolution test chart showing patterns of vertical and horizontal lines with numerical values: 1.0, 1.1, 1.25, 1.4, 1.6, 1.8, 2.0, 2.2, 2.5, 2.8, 3.2, 3.6, 4.0, 4.5, 5.0, 5.6, 6.3, 7.1, 8.0.

The logo for Micro-D, featuring the word "Micro-D" in a stylized, italicized font with horizontal lines through it.

perpendicular distance, x , and the total drift time is:

$$(t - T0) = \int_{X0}^x \frac{dx}{v_d} = \begin{cases} \int_{X0}^x \frac{dt}{k_1 E(z)(1+k_2 E(z)+k_3(E(z))^3)} & E < E_{sat} \\ \frac{x-X0}{v_{sat}} & E > E_{sat} \end{cases} \quad (5.8)$$

To produce the time-to-distance relation Equation 5.8 is inverted:

$$x = RX0 + D(k_1(t - T0), k_2, k_3) \quad (5.9)$$

The steps used to calculate $D(t-T0)$ are outlined in Figure 5.7. Figure 5.7(a) is the calculated field map, $E(x, \phi=0)$, and Figure 5.7(b) is the velocity as a function of x for this field. This is used to calculate the time-to-distance relation shown in Figure 5.7(c) by inverting Equation 5.8.

5.3.2 ϕ and z dependencies

Each sense wire in a jet cell has a particular $E(x)$ and, because they are staggered towards opposite sides of the guard plane, $E(x)$ is different on either side of the anode plane. In addition, $E(x)$ is z -dependent because of the electrostatic deflections. So,

$$E(x) = E(x, z, side)_{wire}.$$

In the prototype studies $E(x, z, side)_{wire}$ was obtained from electrostatic field calculations. The map of $E(x)$ for each side of each wire at different z values was stored in lookup tables that were used as input to the calibration.

A major assumption of the technique is that the electric field map correctly describes the chamber. This required a precise description of the chamber geometry and applied voltages. The relative positions of the anodes were calibrated using tracking data to within $\pm 9 \mu m$ but the positions of the other electrodes were obtained from their nominal positions after gravitational and electrostatic deflections were calculated. Moreover, the position and orientation of the anode plane were also field dependent and the electrostatics calculation was used to determine the

Figure 5.7: Steps in calculating $D(t-T_0)$. (a) $E(x;z;side;\phi=0)$ field map is calculated. (b) The velocity as a function of x is determined from the field. (c) $D(t-T_0)$ is calculated by inverting the distance-to-time relation.

induced rotations or global offsets of the plane. The errors in the drift field would be apparent as systematic deviations of hits from tracks. The question addressed throughout this study was whether or not the electric field calculation was sufficiently accurate to enable one to calibrate the chamber using this physical model.

The study of the systematics of the detector when operated with argon-ethane(50-50) revealed a significant dependence of the time of arrival of the first electron cluster on the angle of the track to the anode plane, i.e. a ϕ dependence. Part of this was associated with the change in direction of the drift of the first electron as described by Equation 5.3 using the parameter R_{iso} .

R_{iso} was approximately equal to half the anode-to-anode spacing and was smaller on the 'far' side of an anode wire relative to the 'near' side. Two parameters, R_{iso}^{near} and R_{iso}^{far} , were introduced to account for this effect.

In addition to the ϕ correction associated with the change in the drift direction of the electrons as they approached the anode the magnitude of the electric field was also ϕ dependent. Because the field used in the time-to-distance relation was calculated for $\phi=0^\circ$, the influence of this ϕ effect on the time-to-distance relation was most severe for large values of ϕ . To minimize this effect only small ϕ angles (less than 10°) were used during these studies.

After including these ϕ and z corrections the x coordinate of a hit in the local coordinates of a cell is:

$$x_{wire} = RXO_{wire} - D(k_1(t - T0), k_2, k_3; \phi; side; z)_{wire} \quad (5.10)$$

Using this technique, a z dependent time-to-distance relation was generated for both sides of each wire in the detector with the following free parameters: VEL, k_2 and E_{sat} and R_{iso}^{near} and R_{iso}^{far} . D_{wire} was calculated at the start of the data analysis and was stored as a lookup table for use throughout the analysis.

There are a number of other smaller effects that can shift the measured electron

arrival time systematically with track distance and orientation whose magnitude cannot be reliably predicted. Included in this class of physical effects is anything that systematically alters the pulse shape with drift distance. The shapes of pulses are expected to be dependent to some extent on x because of a variety of effects:

- the contributions of multiple clusters to the timing of the pulse depends strongly on the isochrones which in turn depend on the drift distance.
- a distance dependent drift velocity in the anode region may systematically alter the shape of leading edge of the pulse.
- diffusion can affect the pulse shape and is a distance dependent effect.
- crosstalk effects can depend on the drift distance (because the velocity depends on drift distance) as well as on ϕ .

The only reliable way for dealing with such effects is to study systematic deviations between a measured hit position and the track on which it lies for tracks with non-zero track slopes.

5.3.3 Gas density scaling

The dependence of the velocity-field relation on gas density was described by Equation 5.2. Since the velocity-field relation is used to obtain the time-to-distance relation, the density dependence can be incorporated into corrections to VEL, k_2 and E_{sat} . If the gas density changes from ρ_a to ρ the three parameters scale as:

$$VEL \propto \frac{\rho_a}{\rho}$$

$$k_2 \propto \frac{\rho_a}{\rho}$$

$$E_{sat} \propto \frac{\rho}{\rho_a}$$

These relations provide a direct connection between monitored changes in gas density and the time-to-distance relation. They were used in the experiments with the prototype to demonstrate that VEL, k_2 and E_{sat} represent properties of the gas and were not simply arbitrary parameters. The results are presented in the next section.

In addition to the ability of this parameterization to accommodate changes in the gas density, VEL also has the ability of correcting for small discrepancies between electrostatic calculation of the field and its true value. This can be of particular value if the wire locations are not known to a high enough precision to prevent significant perturbations to the electrostatic calculation. Once the wire positions and electric fields are properly understood, VEL once again would become a property of the gas and changes to the electric field can be monitored directly and fed into the electric field calculation.

5.4 Calibration with a Cool Gas

5.4.1 Geometry and T0s

The wire positions are a function of the electric field because of the electrostatic deflections. In the hot gas the calibrated wire positions were shown to be in good agreement with the predicted positions from the deflection calculation and the surveys of the detector components. In a cool gas such a direct determination is not easily made because of the dependence of the time-to-distance relation on the field which in turn depends on the wire positions. To overcome this difficulty it was assumed that the deflection calculations provided a sufficiently reliable determination of the relative wire positions. The relative wire positions in each jet cell were calculated separately using the hot gas analysis to determine the positions of the wires at the ends of the detector.

The T0s in the cool gas were determined using the front edge of the TDC distribution as described in Appendix D. Because the velocity changes rapidly as a function of drift distance near the anode wire it was important to limit the number of TDC bins that contributed to the T0 determination. A determination of the T0s using several different sets of data demonstrated that if no more than eight TDC bins (the equivalent of 5 ns) were included in the calculation a reliable T0 measurement could be obtained. After averaging the T0 measurements of each sense wire over the different data sets the uncertainty in T0 became negligible (less than ± 0.1 ns).

5.4.2 Time-to-distance calibration

The electric field, $E(x;side;z)$, was calculated for each wire in a cell having the calculated wire positions at a particular z for $\phi=0^\circ$. The same electric field map was used for both prototype detector jet cells that were studied. This left VEL, k_2 , E_{sat} , R_{iso}^{near} and R_{iso}^{far} to be determined. Because the object of this study was to examine the limits of a calibration based on a physical model of the detector the values for VEL, k_2 , E_{sat} , R_{iso}^{near} and R_{iso}^{far} were obtained initially from 'first principles' in the following manner.

VEL was obtained from the experimental literature[55] while electron transport theory calculations provided an estimate of the saturated drift velocity and field at which saturation occurs in CO₂-isobutane¹². In the 2.5 bar data the initial velocity at 3.2 kV/cm (i.e. VEL) was set to 11 $\mu m/ns$. The saturated drift velocity and field were taken as 80 $\mu m/ns$ and 25 kV/cm. This gave an initial value of 0.05 cm/kV for k_2 .

The values of R_{iso}^{near} and R_{iso}^{far} were determined by using estimates of $(R_{iso}^{near} - R_{iso}^{far})$ and $(R_{iso}^{near} + R_{iso}^{far})$ based on the electrostatic field calculations. $(R_{iso}^{near} - R_{iso}^{far})/2$ was

¹²The saturated velocity was used to determine k_2 once VEL and E_{sat} were fixed.

assumed to be equal to half the distance between adjacent anode wires: 0.25 cm . $(R_{iso}^{near}-R_{iso}^{far})$ was determined by the relative number of field lines terminating on a ‘near’ wire compared to a ‘far’ wire. For the $E_d=3.2, E_a=600\text{ kV/cm}$ electric field configuration the ratio of ‘near’ wire field lines to ‘far’ wire field lines was 1.45. These two conditions set $R_{iso}^{near}=0.31\text{ cm}$ and $R_{iso}^{far}=0.22\text{ cm}$.

A data set was analysed using these initial values of the parameters. Then, the following steps were taken to tune the parameters for the prototype detector.

- The value of VEL was adjusted using the relative wire positions:RX0. This takes advantage of the staggering of the odd and even numbered wires. Since the relative positions of odd and even sense wire planes ($RX0^{odd}$ and $RX0^{even}$) were known to $\pm 3\text{ }\mu\text{m}$ from the deflection calculations they provided a $\pm 0.6\%$ measure of VEL. A correction to the VEL of a jet cell was obtained from the differences in the track residuals, δ_{trk} , of the wires when they were separated into ‘near side’ and ‘far side’ categories:

$$VEL = VEL_{initial} \left(1 + \frac{\delta_{trk}^{near} - \delta_{trk}^{far}}{RX0^{odd} - RX0^{even}} \right)^{-1}$$

- With VEL and R_{iso} fixed, k_2 and E_{sat} were determined by calculating the mean track χ^2 of a set of tracks that pass into the anode region: $\langle \chi^2 \rangle_{track}$. In addition to $\langle \chi^2 \rangle_{track}$, anode crossing tracks were also used in the calibration procedure. A three parameter linear fit (two intercepts, one slope) was performed on each anode crossing track. The hits on one side of the anode plane could have a different intercept from hits on the opposite side but all hits on the line were constrained to have the same slope¹³. In this three parameter linear fit the difference between the intercepts is zero when the time-to-distance relation is correct in the anode region. The mean difference

¹³This is the same technique used to calculate a value for the global ‘T0’ as described in Appendix D. It is demonstrated there that this technique is sensitive to the ϕ of the track because of time-to-distance contributions to the difference in intercepts near the anode-guard plane

in anode crossing intercepts is referred to as Δ_{anz} . The quantity

$$\langle \chi^2 \rangle_{track} + \frac{\Delta_{anz}^2}{\sigma_{\Delta_{anz}}^2}$$

was then minimized by varying k_2 and E_{sat} using the simplex algorithm in the numerical function minimization program *MINUIT*[60]. In each iteration of the minimization process the entire set of tracks were recalibrated with the new k_2 and E_{sat} values and $\langle \chi^2 \rangle_{track}$ and Δ_{anz} calculated.

- Having obtained more accurate values of the parameters the tuning procedure was repeated to ensure that an internally consistent set of constants had been obtained. In practice it was found that convergence was achieved within a single iteration.

Note that there was little evidence that R_{iso} needed further tuning so the initial values were maintained.

After performing this calibration the value of VEL was within 1% of the initial value of $11 \mu m/ns$. The values of k_2 and E_{sat} at 2.5 bar were $0.07 \pm 0.01 \text{ cm/kV}$ and $29 \pm 1 \text{ kV cm}$ respectively¹⁴.

Independent calibrations of several sets of data revealed that the velocity, normalized by the measured gas density, increased steadily by approximately 1% over the eight hour period following the addition of CO₂-isobutane gas to the pressure vessel. The cause of the changing velocity was not known but the most likely explanation attributed it to the release of contaminants into the gas over a period of time. One potential source of contamination was argon-ethane(50-50) with which the pressure vessel was filled prior to being filled with the CO₂-isobutane(80-20). If some of that gas was trapped inside the pressure vessel (eg. inside the signal and high voltage cables) and was slowly replaced by the CO₂-isobutane(80-20) the velocity would tend to increase over time.

¹⁴These values suggest that the drift velocity saturates at a value of $110 \pm 10 \mu m/ns$.

One interesting aspect of this increasing velocity was that it provided a means of testing whether or not the form of the time-to-distance relation that was used could easily accommodate such effects. In fact, the changes were quite easily calibrated out by simply using this method of measuring changes in the apparent stagger of the anode wires.

5.4.3 Evaluation of the calibration

To evaluate this calibration technique three 'calibration monitors' were used:

1. The mean slope of the beam tracks measured relative to the anode-guard plane as a function of the x-coordinate of a central wire.
2. The mean track residuals of all wires in a jet cell as a function of drift distance separated into the 'near' and 'far' sides of each wire. A negative drift distance was assigned to hits on the 'far' side of each wire.
3. The gaussian sigma of the track residuals of all wires in a jet cell combined over all drift distances.

The gaussian sigma of the mean track residual distribution provided a global evaluation of the calibration and was used to assign a quantitative value to the systematic errors not accounted for in this model. A plot of the mean track residual as a function of signed drift distance can reveal systematic effects that affect all wires in the same way and is particularly sensitive to a failure to calibrate the 'effective stagger' that is produced when the time-to-distance relation is incorrect.

The measured slope as a function of x was useful because it evaluated whether or not an absolute calibration had been achieved. With an appropriate calibration of the chamber the measured slope was independent of x because a collimated test beam was used. Recall that the measured slope is proportional to the assumed drift velocity. If the time-to-distance relation was correct in the uniform field region but

was incorrect in the anode region then the measured slope changes as a function of x in the anode region.

Another effect that is sensitive to this 'monitor' is a radially varying drift velocity. For example, if the drift velocity increases with wire number and this has not been accounted for then the measured slope would increase as a function of drift distance. A measured slope that is uniform across the cell indicates that there is no evidence for a systematic radial variation in VEL.

An example of the appearance of these three 'monitors' when the initial, untuned, values of the parameters were used is presented in Figure 5.8. The measured $\tan \phi$ and mean track residual are uniform over most of the drift gap but change in the anode and cathode regions. This is an indication of a failure of the time-to-distance relation to provide a correct absolute spatial measurement in these parts of the detector. The result is that the distribution of combined residuals has a sigma considerably larger than intrinsic resolution. All other plots of the 'calibration monitors' are for sets of data after the calibration procedure was completed. The differences are self evident: the $\tan \phi$ and mean track residual are nearly uniform across the cell and the distribution of residuals are close to the intrinsic resolutions.

Evidence that absolute calibrations were achieved using this technique were provided by a comparisons of the measured slopes of beam tracks in adjacent jet cells. If the $D(t-T_0)$ was correct the difference in measured slopes in adjacent jet cells would be equal to surveyed value of Φ_{anode} . Using the calibration method described here, the difference in measured slopes was different from Φ_{anode} by 0.59%. The error on the surveyed value of Φ_{anode} was 0.34% which means that the measured value using tracking was less than 2 standard deviations from the surveyed value.

The reason for using the VEL, k_2 and E_{sat} parameters was to provide a means of introducing the drift velocity into the model. To demonstrate that these parameters

Figure 5.8: Uncalibrated example of plots of the 'Calibration Monitors' (measured track slope vs x , mean track residuals vs drift distance, and combined residuals) for the initial values of the time-to-distance parameters. The poor calibration is evident as non-uniform slope, and mean residuals as well as poor resolution.

fulfilled that role the pressure was increased between 2.0 and 2.5 *bar* and the initial parameter values were adjusted according to the gas density scaling described in Section 5.3.3. The plots of 'calibration monitors' for the pressures at 2.0, 2.2, 2.4 and 2.5 *bar* are presented in Figures 5.9 to 5.12. Because of effect of the contaminants mentioned above the density scaling property could only be accurately tested for data sets taken within several hours of each other. This was the case for the the 2.4 and 2.2 *bar* data sets. The parameters were tuned for the 2.4 *bar* data set and adjusted by the density scaling for the 2.2 *bar* data set without any further tuning. The calibration results presented in Figure 5.10 reveal that this was entirely satisfactory. Other changes in density were accounted for to better than 1% using the density scaling of the parameters.

The distributions of track residuals of all wires over all drift distances provide a means of quantitatively evaluating the contributions to the resolution from various systematic effects. The full-width-at-half-maximum (FWHM) sigma of the distributions provide a reasonable estimate of the resolution in the uniform field region when they are corrected for the fact that all hits are included in the track fits¹⁵. Intrinsic resolutions obtained from triplet distributions and the resolutions obtained from the track residuals are tabulated in Table 5.2. By subtracting in quadrature the triplet resolution from the track residual resolution the contribution of systematic effects to the resolution are obtained. Included in such effects are the true values of the velocity parameters for this gas, the true electric fields and the exact positions of all wires in the cell. The lack of precise knowledge of these parameters (as well as others) provide a 15 μm contribution to the resolution. Such a small degradation indicates that the model of the detector used to develop the

¹⁵The distribution sigmas are multiplied by

$$\sqrt{\frac{\text{no. of wires}}{\text{no. of wires} - 2}}$$

to obtain the resolution.

Figure 5.9: Plots of the 'Calibration Monitors' (measured track slope vs x , mean track residuals vs drift distance, and combined residuals) for a pressure of 2.0 bar.

Figure 5.10: Plots of the 'Calibration Monitors' (measured track slope vs x , mean track residuals vs drift distance, and combined residuals) for a pressure of 2.2 bar.

Figure 5.11: Plots of the 'Calibration Monitors' (measured track slope vs x , mean track residuals vs drift distance, and combined residuals) for a pressure of 2.4 bar.

Figure 5.12: Plots of the 'Calibration Monitors' (measured track slope vs x , mean track residuals vs drift distance, and combined residuals) for a pressure of 2.5 bar.

Pressure (bar)	Track Residual Resolution (μm)	Triplet Resolution (μm)	Systematic Contribution (μm)
2.0	32.9	28.9	15.7
2.2	30.7	27.5	13.6
2.4	29.6	25.8	14.5
2.5	28.5	24.2	15.0

Table 5.2: Evaluation of the contribution of systematic errors to the absolute resolution of the detector. These are obtained by subtracting the triplet resolution from the track residual resolutions in quadrature.

time-to-distance relation is adequate.

The time-to-distance relation of the 2.5 bar CO₂-isobutane data was calculated initially for the centre of the detector ($z=0$). But because the electric field in the anode region changed significantly as a function of z an examination of tracks at different z probed the ability of the model to describe the change in field. This property came from the z dependence of the sense wire position which was produced by the electrostatic bowing. Plots of the 'calibration monitors' were made for a data set at large z . The different electric field was introduced by calculating the $E(x;side;z)$ map at the new z . The resulting plots are presented in Figure 5.13. The uniformity of the slope and mean residual plots indicate that $D(t-T_0)$ is satisfactory and provides additional evidence that the parameters intended to describe the velocity-field relation accomplish that task.

As mentioned in Section 5.3.2 as ϕ increases the field map for $\phi=0^\circ$ is expected to provide a less reliable description of the chamber. This would be evident when larger values of ϕ are studied. Figures 5.14 and 5.15 both display the 'calibration monitors' for a ϕ of 6.3° . Some indication of this is evident as a slight drift distance dependence for the mean residual plots but it is at a very low level.

Figure 5.15 is a plot at $\theta = 50^\circ$. A significant broadening of the residual distribution as compared to the $\theta = 90^\circ$ case of Figure 5.14 suggests that there are additional systematic effects associated with the smaller θ . These may be associ-

Figure 5.13: Plots of the 'Calibration Monitors' (measured track slope vs x , mean track residuals vs drift distance, and combined residuals) for a pressure of 2.5 bar at $z = 40 \text{ cm}$.

Figure 5.14: Plots of the 'Calibration Monitors' (measured track slope vs x , mean track residuals vs drift distance, and combined residuals) for a pressure of 2.5 bar for $\phi = 6.5^\circ$.

Figure 5.15: Plots of the 'Calibration Monitors' (measured track slope vs x , mean track residuals vs drift distance, and combined residuals) for a pressure of 2.5 bar for $\theta = 50^\circ$.

ated with the different pulse shapes that a smaller θ introduces. The nature of the effects were not investigated further but it was evident that they contributed approximately $15\mu m$ (in quadrature) to the absolute resolution in addition to the $15\mu m$ systematics of the $\theta=90^\circ$ case.

5.5 Vertex Detector Calibration at LEP

The calibration techniques described here have been shown to work reliably with the prototype detector in the test beam. The ability to transfer these methods to the OPAL vertex detector at LEP cannot be entirely determined until OPAL experimental data exists. However, a number of characteristics of the LEP environment are different from the test beam and some of these are identified here.

During the prototype beam tests the z of a hit was set by the known beam location. Because both $RX0(z)$ and $D(t-T0;\phi;side;z)$ are z dependent it is important to know the z of each hit. At LEP the time-difference measurement must be used to provide an initial measurement of z when converting the drift time to a distance. The conversion relation between the time-difference measurement and z value was mentioned in Chapter 4. This relation may be calibrated without a test beam by using the high precision z measurements provided by the stereo cell. If the time-difference z measurement is too coarse it may be necessary to iterate on the $D(t-T0;\phi;side;z)$ calculation where in the first pass the time-difference z is used and in the second pass the stereo z is used. Whether or not this technique is required depends on the size of the electrostatic deflections, the precision of the time-difference z and the sensitivity of $D(t-T0;\phi;side;z)$ to z .

The central detector of OPAL will operate in a $0.4T$ magnetic field. This produces two new effects to consider, the Lorentz angle, θ_L , and the magnetic field velocity, v_m . For argon-ethane(50-50) operated with a drift field of $3.5kV/cm$ and pressure of $4bar$, $\theta_L \sim 20^\circ$ and the velocity changes by 6%. Using CO_2 -isobutane(80-

20) with the same field and pressure $\theta_L \sim 2^\circ$ with less than a 0.1% change in the velocity in the uniform field region but these numbers change significantly with field and therefore will be drift distance dependent.

To obtain an absolute calibration of the detector it will be necessary to use the external constraints provided by the OPAL Jet Chamber. The Jet chamber is itself calibrated with a laser beam system. In addition, cosmic rays and e^+e^- events in which e^+e^- or $\mu^+\mu^-$ form the final state provide very clean calibration constraints which can be used in a 360° vertex detector for self calibration. In the case of cosmic rays, usually more than one vertex jet cell measures the same track thereby providing powerful constraints on the time-to-distance calibration. For dilepton events, the event topology of two back-to-back tracks which traverse opposite vertex jet cells provides an equally attractive calibration tool. A 360° vertex detector in OPAL will have many external constraints available to provide a reliable calibration of the detector.

5.6 Summary

It was demonstrated in this chapter that the physical effects that influence the absolute resolution of a minijet drift chamber can be described with sufficient precision using a very simple model. The model depended on the reliability of the calculations of the electrostatic field and an accurate description of the geometry of the detector.

The x-coordinates of the wire positions within a jet cell were determined using a gas with a saturated drift velocity while the survey of the detector was used to constrain the position and orientation of one jet cell relative to another. It was demonstrated that the calculation of the electrostatic deflections of the sense wires in the detector were in agreement with the measured positions at the $\pm 10 \mu m$ level. This demonstrated that a measureable quantity that depended strongly on the

electrostatics could be accurately described by the electrostatic field calculations.

Using a calculated electric field map of the detector, a time-to-distance relation was developed that depended only on the dependence of the velocity on the electric field. It was demonstrated that this relation scaled appropriately with gas density and with changes in the electric field. The success of a physics based calibration of the detector has demonstrated that the operation of a minijet cell with a gas having an unsaturated drift velocity is a viable option for obtaining high spatial resolution measurements.

Chapter 6

The 360° Detector: Final Design and Initial Test Results

The general design of the 360° detector was essentially the same as that of the prototype but details of the design incorporated modifications that were motivated by the results of the prototype studies. Many of these changes were a direct consequence of the 25 μm resolution obtained using CO_2 (80%)-isobutane(20%) at 2.5 bar pressure. If this very good resolution were to be accessible to a detector operating between 3 and 4 bar, which was the potential range of pressures in the operation of the OPAL Central Detector, a variety of changes in the design would be required. Other modifications were introduced to decrease the 'near wire - far wire' asymmetries in the detector response, while yet other changes were introduced to simplify the implementation of the solutions to various mechanical and high voltage problems. These are discussed in Section 6.1. The 360° detector was constructed during 1987 and 1988 with the initial tests performed during the summer of 1988. A summary of the initial test results of the detector are presented in Section 6.2.

6.1 Design Modifications

6.1.1 Electrostatic associated modifications

For the detector to operate with CO₂-isobutane gas at a pressure between 3 and 4 bar a number of modifications to the detailed design were required. These were intended to accommodate the higher voltages that had to be placed on the detector in order to obtain a useful gas gain at the elevated pressures.

To ensure flexibility in the choice of a cool gas the design goal was to maximize the anode surface fields of the detector. The anode surface field depends on both the value of the drift field and guard wire surface fields. Increasing the gas gain through an increase in the guard surface field requires an increase in the anode-guard voltage difference. An anode surface field of 700 kV/cm can be approached for drift fields below 3.3 kV/cm only if the anode-guard voltage difference exceeds 4.0 kV[61]. However, there was no evidence from the prototype studies that the detector could be operated safely with such large voltage differences between the anode and guard wires. The largest anode-guard potential difference that was applied to the prototype was 3.29 kV. This was used throughout the period when 2.5 bar CO₂-isobutane(80-20) data was taken when the drift and anode surface fields were 3.2 kV/cm and 600 kV/cm respectively. If the prototype tests are used to set the limit on anode-guard potential difference then the only way to increase the anode field would be to increase the drift field. The desire to operate the detector with large anode-guard potential differences and drift fields in excess of 3.2 kV/cm motivated several design modifications.

- On the locating combs the anode-guard separation was only 2.65 mm in the axial cells and 2.50 mm in the stereo cells. For the insulators used in the chamber construction (G10 and plexiglass), a high voltage breakdown can occur across two points at different potentials if they are in contact through

the surface of the insulating material that separates them¹. To ensure that surface breakdown would not limit the anode-guard voltage difference the surface path length between the anode and guard grooves on the wire locating combs was increased.

- The drift fields would also be increased above the 3.2 kV/cm value that was used in the prototype in order to attain the higher anode surface fields with a minimal increase in the anode-guard voltage difference. As discussed in Chapter 4 the magnitude of the anode deflections rose exponentially with drift field within this operating region in the prototype and operation beyond 3.2 kV/cm was avoided for that reason. The field at which the exponential behaviour becomes a significant wire positioning systematic uncertainty can be increased if the initial anode offset on the comb is reduced. The stagger was reduced in the final design from $150\text{ }\mu\text{m}$ to $41\text{ }\mu\text{m}$. This modification is driven by other factors as well which are discussed later.
- At the higher drift and anode fields, the cathode-like surface fields on the cathodes, guards and field shaping wires would exceed 20 kV/cm unless the surface area on most of these wires was increased. The size of most cathode wires were increased from the $100\text{ }\mu\text{m}$ diameter of the prototype to $125\text{ }\mu\text{m}$. The guard wires were increased from $100\text{ }\mu\text{m}$ to $200\text{ }\mu\text{m}$. The diameters of other wires varied from $100\text{ }\mu\text{m}$ to $200\text{ }\mu\text{m}$ depending on their positions in the cell.

Even with these modifications incorporated into the final design, the maximum anode surface field that could be placed on the detector in the axial cells without introducing significantly more than 20 kV/cm on the cathode-like wires is 620 kV/cm .

¹For G10 and plexiglass this typically occurs if more than a 1 kV voltage difference is applied for every 1 mm of surface path length separating the two points.

This can be accomplished if the drift field is 3.6 kV/cm and would require a 3.21 kV potential difference between the anode and guards[61].

6.1.2 Crosstalk associated modifications

The prototype studies revealed that the response of the detector was asymmetric with respect to 'near' and 'far' hits. The hits that are associated with particle tracks on the 'far' side of an anode wire had a poorer resolution than those that originated on the 'near' side. This was shown to be a result of residual crosstalk in the chamber. The asymmetry manifested itself most dramatically in the time difference measurement's 'z-splitting' effect. To minimize these crosstalk effects the final design incorporated several modifications and new features.

- The effects of crosstalk had been partly accounted for in the prototype by installing compensation resistors linking neighbouring anode wire channels on the preamplifiers. A small proportion of the signal was purposely fed to adjacent channels in an attempt to cancel the opposite polarity induced crosstalk that occurs in the chamber itself. The proportion of the signal sent to the adjacent wire in the prototype was chosen on the basis of experience gained from work on chambers with different geometries. The values for the final design were determined by measuring the crosstalk in the OPAL vertex prototype with the compensating resistors removed from the preamps. The geometries of the prototype and final detector are essentially identical and so the optimum crosstalk compensation is provided in the final design.
- It was demonstrated in Chapter 4 that the influence of the crosstalk was a strongly peaked function of the difference in arrival times of the electrons on adjacent wires. Ideally, the difference in arrival times ought to be as large as possible to avoid any pulse overlap. Unfortunately, the classic jet chamber design cannot easily accommodate such a feature. One possibility would involve

increasing the anode stagger to ensure that neighboring pulses don't overlap, but the electrostatic constraints, mentioned above, rule out such a solution. The alternative was to move towards smaller differences in arrival time. This was done by decreasing the anode stagger. Elimination of the crosstalk effects is not ensured by this but it does produce a reduction in them, as was made clear in the argon-ethane crosstalk studies presented in Chapter 4. The anodes in the final design were given a stagger of $\pm 41\mu m$, or a decrease by a factor of more than three as compared to the stagger in the prototype.

- The last technique employed to minimize the effects of crosstalk between anodes was to provide signal termination at both ends of all pairs of cathode wires. The lack of termination of the cathodes in the prototype was likely responsible for some of the observed signal distortion in later arriving pulses. The implementation of this termination in the final design involves the installation of a resistor-capacitor network on a removable board connected to the ends of the cathodes. If there is little evidence for improved detector performance with this termination the capacitors can be removed. This is desirable because the energy stored in the capacitors can potentially damage the chamber should a high voltage breakdown between the cathode and an anode wire occur.

6.1.3 Electronics improvements

The two hit resolution of the detector is partially limited by the long pulse tails. The influence of this was reduced by differentiating the pulse in the preamplifier. A pole-zero network was used as a means of preventing undershoot from differentiating the initially differentiated pulse². In the prototype this was adjusted for hot gas running. To minimize the effects of the longer tail which exists when a cool gas

²The pulse is first differentiated at the end of the wire via the preamp termination.

is used, a larger degree of differentiation was required. This involved re-tuning the pole-zero network for cool gas operation and this was incorporated into the final design. In addition, to reduce the refiring of the discriminator on the pulse tails a new feature of the discrimination circuit effectively inhibited refiring of the discriminator for a fixed period of time after the initial detection of a pulse.

The evaluation of the performance of the electronics demonstrated that there was a significant degradation in the intrinsic resolution of the TDC as the TDC values increased. This was traced back to difficulties with the clock used in the TDC³. Improvements in the detailed implementation of the TDC clock were performed in the final design.

6.1.4 Control and monitoring of systematics

It has been shown that intrinsic resolutions of the order of $30\ \mu\text{m}$ can be achieved in the detector. The ability to translate this into measurements of space points with the same level of resolution requires control of the various systematic errors below this level. Chapter 5 provided a technique for incorporating various systematics into the time-to-distance relationship, but it is clear from that presentation that the close coupling of wire position to the electric field and hence to the time-to-distance relationship makes this task difficult. Prior knowledge of the positions of the wires and particularly the position and orientation of the anode and cathode planes would greatly improve the ability to access the calibrations efficiently. This can be accomplished by calibrating positions using a saturated gas, as was done in the prototype. If, however, the positions are well known to begin with the saturated gas calibration can be used as a redundant measurement and potentially can be used to study additional systematics. For this reason, the combs and dowel holes were built and measured to provide positioning constraints at the $10\ \mu\text{m}$ level.

³This task was performed by the individuals who designed the electronics at the Rutherford Appleton Laboratory.

Use of a cool gas and the quest for the highest resolution necessitates the monitoring of all factors that can change and influence the time-to-distance relationship. These requirements resulted in the placement of a set of temperature monitors in the G10 end plates of the detector. A profile of temperature gradients at the ends of the detector can be measured at the $\pm 0.5^\circ\text{C}$ level with these devices in place. High resolution absolute pressure monitoring has also been incorporated into the final design thus ensuring that the most significant systematic contributions to the final resolution will be monitored.

6.2 Initial Tests and Performance

The construction of the detector was completed in the spring of 1988. The initial test period and debugging has continued from that time until the present (autumn 1988). A number of problems have been found and solved in the implementation of the final design. Among the more dramatic problems uncovered during the test period was a high voltage breakdown between a stereo field ring wire and an aluminum ring placed in a groove in the insulating G10 endplate. The aluminum ring is used to constrain the carbon fibre tube in 'z' thereby forming the mechanism for keeping the endplates apart. The unusual aspect of the problem was that the high voltage breakdown occurred *through* the G10. The voltage between the two points was 8.1 kV/cm and the breakdown was through 2 mm of G10. It was believed that this failure was associated with a local flaw in the G10. Unfortunately, this failure has so far prevented operation of the detector with CO_2 -isobutane (80-20) at pressures higher than 2.0 bar .

The prototype results have demonstrated the advantage of using a gas with a low drift velocity but the unfortunate failure mentioned above restricted operation of the chamber in the immediate future to a high gain gas. 'JADE' gas (argon(89%) - methane(9%) - isobutane(2%)) is a hot gas and has a velocity-electric

Gas	Pressure (bar)	Drift Field (kV/cm)	Anode Field (kV/cm)	Drift Velocity ($\mu\text{m/ns}$)	r- ϕ Triplet Resolution (μm)
CO ₂ (80%) isobutane(20%)	2.0	3.0	520 and 540	12.9	38.3 $\pm$ 0.7
argon(50%) ethane(50%)	3.0	2.8, 3.0 and 3.2	499 and 509	53	65.9 $\pm$ 0.3
argon(50%) ethane(50%)	4.0	3.0, 3.2 and 3.4	549	53	62.0 $\pm$ 1.2
argon(88%)-methane(10%) isobutane(2%)	4.0	3.4	410	36	56.2 $\pm$ 1.0

Table 6.1: Summary of r- ϕ Resolutions as Measured in the Axial Cells of the 360° Chamber [62].

field dependence typical of argon-based gases in that it has a Ramsauer-Townsend 'peak'. However, on the high field side of the peak the velocity drops more steeply than in many hot gases and provides a slowly varying but reduced velocity. The chamber was operated with this gas at 4 bar pressure and with drift fields high enough to access a velocity of 36 $\mu\text{m/ns}$.

6.2.1 Gas studies

Cosmic ray data was collected during initial tests of the detector during the spring and summer of 1988 in Ottawa. Most of the data was collected with the chamber filled with 4 bar JADE gas. In addition, the chamber was operated with argon(50%)-ethane(50%) up to 4 bar and with CO₂(80%)-isobutane(20%) up to 2 bar. The r- ϕ triplet resolutions averaged over various sectors is presented in Table 6.1[62]. At the level of simply examining the combined cosmic data, which include all track angles, resolutions measured in this detector are entirely consistent with expectations based on the prototype studies.

6.2.2 Resolution studies with JADE Gas

Further cosmic ray studies of the detector were performed at CERN in the autumn of 1988[63]. Among these studies was an investigation of the response of the detector when it was operated using JADE gas with reduced gas gain. The resolution studies used track residuals with the time-to-distance relation calibration performed using the electric field map technique similar to that described in Chapter 5. As mentioned above, in JADE gas the velocity on the high side of the Ramsauer-Townsend peak depends on the electric field so the field map technique was useful for determining the time-to-distance relation in this gas. Wyatt[63] used a parameterization of the time-to-distance relation:

$$x = a(1 - e^{-b(t-T0)^{1.3}}) + c(t - T0)$$

at $z=0$ for an anode field of 380 kV/cm and drift field of 3.2 kV/cm . The drift velocity in the uniform field region was $35.7 \mu\text{m/ns}$ and only data within 15 cm of the centre of the wire was used. Other cuts on the data were that the track ϕ angles relative to the anode planes were restricted to be less than 10° and only tracks with θ greater than 70° were used. In addition, only hits with deviations from the track less than 4 standard deviations away were kept. Plots of both $r-\phi$ and z resolution as a function of anode surface field are presented in Figure 6.1. The gas gain over this range of anode surface fields is lower than those used in the prototype by roughly a factor of two.

From the lower plots one observes that just as in the prototype the time-difference resolution improves with increasing gas gain. Also as with the prototype the $r-\phi$ resolution shows little dependence on gas gain when the pulses are sufficiently large. At reduced gain the signal-to-noise effects also degrade the $r-\phi$ resolution. For anode surface fields greater than 350 kV/cm the detection efficiency was greater than 95% for appropriate discrimination noise thresholds. At the 350 kV/cm point the detection efficiency dropped to roughly 85% for the lowest noise threshold tested.

Figure 6.1: R- Φ and Z intrinsic resolution as a function of anode surface field in 4 bar JADE gas[63].

6.2.3 Z-splitting

A number of the modifications incorporated into this design were motivated by the desire to reduce the crosstalk that was responsible for the 'z-splitting' effects in the time-difference measurements. In particular, the significant reduction in the stagger effectively shifts the crosstalk Δ_{Arrival} time to a less sensitive regime and the inclusion of cathode termination in addition to guard wire termination were motivated by crosstalk considerations. The requirement for appropriate wire termination in this chamber design was once again verified in the 360° detector when an error in the construction revealed that only one end of the guard wires were terminated. The 'z-splitting' effect was present in that case. Once the appropriate terminations were applied the 'z-splitting' effect was eliminated.

6.3 Summary

The prototype studies have been used to provide an understanding of the OPAL minijet vertex detector design at a level that permits quantitative predictions to be made about its performance. A series of detailed modifications to the design were introduced as a consequence of the information that has been obtained from those studies. The response of a 360° chamber in which the final design has been incorporated is entirely consistent with expectations based on the results of the experiments with the prototype.

Chapter 7

Conclusion and Discussion

7.1 Resolution Limits with the OPAL Minijet Vertex Detector

The factors that limit the ultimate resolution that can be achieved using a minijet drift chamber design have been investigated in experiments using a vertex detector prototype.

Use of a gas having a saturated drift velocity avoids many systematic problems but the relatively high saturation velocity, initial ionization properties and diffusion limit the intrinsic resolution obtainable with such gases to between 50 and 60 μm . The diffusion can only be reduced by increasing the pressure and reducing the electron drift length. A minijet cell design loses much of its attractiveness if the anode-cathode gap becomes so small that the anode region field non-uniformities dominate the electrostatics of the cell. For the inner radius wires in the OPAL vertex detector the nonuniform region occupies nearly 30% of the drift gap. A smaller drift length cannot be justified for a minijet design. In practice, the pressure cannot be arbitrarily increased because of the difficulties involved in providing the higher voltages required to operate at elevated pressures. As mentioned in Chapter 6, such practical problems have become a significant feature in the choice of gases

and operating conditions in the 360° detector. In addition, the increase in the multiple Coulomb scattering that accompanies an increase in pressure degrades the momentum measurements performed by the Central Detector. A pressure of 4 bar is a practical limit for a minijet vertex detector in OPAL. The results from the prototype have shown that there is very little gained in resolution from increasing the pressure once 3 bar has been reached. The contribution to resolution from diffusion has been minimized within the design of this detector from the point of view of pressure and drift length. The other factor that limits the resolution is the relatively high saturation velocity of those gases that do saturate. Nonuniform pulse shapes that are associated primarily with fluctuations in electron cluster sizes introduce a degradation to the timing measurement on the order of 1 ns. Although the pulse uniformity may be improved by operating with gains approaching the limited-streamer operation, such an operation is impractical in a minijet chamber in which multiple hit measurements are required. An alternative method is to operate with a leading-edge threshold discriminator with the threshold turned down as low as the noise permits. This was done in the prototype and the resolution of hits uninfluenced by crosstalk ('near' wire hits) was between 45 and 50 μm . Unfortunately the time-difference resolution, which is strongly dependent on the noise, is significantly degraded when this method of timing is used. The high electron drift velocity implies that the spatial resolution is limited to approximately 50 μm within the constraints of the design.

A method for overcoming the intrinsic limitations of a saturated gas is to operate the chamber with an unsaturated but cool gas. With a cool gas the lower velocity provides an improved spatial resolution with the same timing resolution as that obtained with a hot saturated gas. Although the intrinsic diffusion of a cool gas is significantly lower than that of the hot gases, the improvement in resolution is sufficiently large that diffusion becomes a dominant limit to the resolution that can be obtained with a cool gas. At 2.5 bar an intrinsic resolution of 25 μm was ob-

tained with the prototype detector. At this level of resolution the systematic effects associated with operating the detector with an unsaturated gas become an equally serious concern. However, it has been demonstrated that many of the systematics can be incorporated reliably into a physical treatment of the time-to-distance relation. Coupling this treatment with careful monitoring of the pressure, temperature, gas composition and velocity-field properties provides a viable technique for attaining the optimal resolution.

7.2 Further Design Considerations

Through the process of studying the prototype of a minijet vertex detector and moving towards the final design and implementation in the 360° chamber there has been much experience gained in addressing practical problems that motivate consideration of further design modifications. The advantages of using a jet cell design have been recognized and, indeed, re-enforced throughout this process. Use of a cool gas in a jet chamber, with its well defined electrostatic properties, should now be considered as a viable option that can significantly improve the resolution. The degree of improvement depends only on how much effort is spent on understanding and accounting for the systematic effects at the level of the higher intrinsic resolutions now attainable.

However, accepting that a jet chamber operating with a cool gas is a viable design, there are aspects of the basic design that can be reviewed. In practice, the design is sufficiently complex and the required voltages sufficiently high that the reliability of the operation must be seriously reviewed. To this end, any features that simplify the high voltage implementation are desirable. An example of such a simplification would involve operating the cathode planes at ground potential with the anode wires placed at positive high voltage. The advantage here is the elimination of the cathode resistor chains and the problems of AC decoupling of the

cathodes. Another change would be to increase the distance between anode and guard wires. This would enable higher potential differences to be placed on the guard wires and thereby increase the operating range of the chamber.

The cathode boundary effects in the chamber can be reduced and the construction simplified by using a design that uses a larger anode-cathode gap. The resolution losses associated with diffusion would have to be weighed against the gains made by having a smaller solid angle associated with the anode and cathode wire regions. Another method of minimizing boundary effects may involve use of foils for the cathode planes. This, of course, would require a significant amount of work directed towards the development of the appropriate foil technology.

A decision to operate with a cool gas opens up the option of using a flash ADC (FADC) readout. The currently available FADC speed (100 MHz) is sufficient to be of use with the slower drift velocities. One consequence of this is that it permits charge division to be used to measure the coarse z instead of the time-difference. Charge division is much less sensitive to the details of the transmission line and noise properties of the chamber than a time-difference measurement and would provide a more robust measurement for that reason. In addition, the two hit resolution of the detector can be improved because a FADC allows for analysis of pulse pairs that would not normally retrigger a low threshold hardware discriminator.

Another consideration is to introduce an azimuthal tilt to the cells which would ensure that some tracks cross a boundary plane in the LEP environment. One advantage of this is that there would be a large number of tracks useful for self calibration purposes. A more significant advantage is that in such a design only a small number of hits on a track would have the poor anode region resolution, whereas in the current design, any track close to an anode has all hits with a poorer resolution.

7.3 Summary

The Standard Model of fundamental processes has provided a theoretical framework that can be challenged effectively by experimenting with e^+e^- annihilations at the Z^0 pole. These experiments will be performed by the OPAL collaboration at LEP using a detector that has been designed to measure the momentum and identity of all electromagnetically interacting particles and the energy of all strongly interacting particles created in the annihilation and subsequent Z^0 decay. Events in which the τ lepton and hadrons containing c and b quarks are produced will be identified at OPAL by the presence of secondary decay vertices near the interaction point. This task requires the use of a high resolution charged particle tracking 'vertex detector'. The prototype of the OPAL vertex detector had been built and detailed studies of this detector have provided the ability to quantitatively predict the response of the final design of the detector and to provide modifications in the details of the final design.

With $3\frac{3}{4}$ bar pressure argon(50%)-ethane(50%), which was operated in a region in which the electron drift velocity is approximately independent of the applied electric field, a drift distance spatial resolution of $60\mu m$ was attained. This resolution was limited primarily by the fluctuations in shapes of the chamber pulses resulting mainly from fluctuations in the size of electron clusters. A Monte Carlo simulation of the detector supported this evaluation of the limitation of the intrinsic resolution. One method for improving this involved using a gas with a lower drift velocity. CO_2 (80%)-isobutane(20%) at 2.5 bar pressure was operated with a drift velocity nearly five times slower than argon(50%)-ethane(50%) and with this gas a $25\mu m$ resolution was achieved. A difficulty with CO_2 (80%)-isobutane(20%) was that the drift velocity depends strongly on the electric field. This problem was addressed by developing a model of the detector that used precision measurements of the wire positions to calculate the electric fields in the detector. Using these calcu-

lations together with a parameterized dependence of the drift velocity on the field, a simple calibration technique was developed which preserved most of the intrinsic resolution.

To obtain a coarse measurement of the coordinate orthogonal to the drift direction the difference in the arrival time of a pulse at opposite ends of each sense wire was used. It is shown that this technique is limited by signal-to-noise effects. Under optimal conditions (no cross talk and maximum gas gain) the end-to-end time difference technique provided a measurement with a resolution of 100 ps which is equivalent to a spatial resolution of 2 cm. This was obtained in the argon(50%)-ethane(50%) gas. In the CO₂(80%)-isobutane(20%) gas, which had smaller signals, the best resolution attained was 3.5 cm. It is evident from this that time-difference measurements of the orthogonal coordinate require early amplification stages to have either high gain or low noise for optimal operation.

The experiments with the prototype demonstrated that this detector design has the potential for obtaining point resolutions better than 30 μ m if a gas with a reduced drift velocity is used. A detector with such a resolution will be of considerable value when addressing the task of identifying the high momentum particles associated with the decay of τ leptons, charm and beauty.

Appendix A

The OPAL Detector

A global picture of OPAL has been described in Chapter 1 and some details of the CD have been discussed in Section 1.3. In this appendix details of the rest of the the detector are presented.

The electromagnetic calorimeter detects and measures the energy of electrons and photons. The barrel calorimeter around the solenoid covers 82% of 4π (down to $\theta = 34.6^\circ$). It consists of 9440 lead glass blocks, each pointing approximately towards the interaction point. The Cherenkov light produced in the electromagnetic showering is detected at the back of each block with a photomultiplier tube (PMT). Each block is 37 cm or 21.8 radiation lengths long and samples 2.25° in ϕ and approximately 2° in θ ¹. The back face of a block is 10 cm $\times$ 10 cm and the front surface is smaller with a cross section that is not an exact square. Studies with test modules have measured an intrinsic energy resolution (σ_E/E) of $(4.0/\sqrt{E [GeV]} + 1.5)\%$ and spatial resolutions of 7.5 mm for 3 GeV electrons decreasing to 2.5 mm at 30 GeV. Each endcap calorimeter is composed of 1250 lead glass blocks oriented parallel to the beam axis covering 15% of the solid angle down to approximately $\theta = 15^\circ$. The light is detected using single stage PMTs, called vacuum phototriodes, which operate in magnetic fields in excess of 1.0 Tesla which is necessary as the field in

¹The precise sampling in θ is θ dependent.

this region is nearly the same as it is in the centre of the magnet. Each block is twenty-two radiation lengths deep and has a $90 \times 90 \text{ mm}^2$ cross section². A spatial resolution of 11 mm at 1 GeV decreasing to 7 mm at 10 GeV is expected and an intrinsic energy resolution of $6\%/\sqrt{E [\text{GeV}]}$ has been measured with test modules.

The forward detector has as a subcomponent a lead-scintillator calorimeter with an anticipated energy resolution of $17\%/\sqrt{E [\text{GeV}]}$ and spatial resolution of between 5 and 15 mm. This increases the solid angle electromagnetic calorimetry coverage to 99.9%. The forward detector also has charged particle tracking drift chambers with a 1 mm resolution and small angle precision luminosity monitors formed by a set of scintillators. The forward detector is used in the study of two photon physics which requires detection of slightly scattered electrons and for luminosity measurements based on small angle Bhabha scattering.

The coil and pressure vessel together constitute 1.5 radiation lengths of material before the calorimeter. One of the effects of this is to degrade the electromagnetic energy resolution for energies less than 20 GeV . For example at 1 GeV the resolution is degraded by nearly a factor of three (to 11%). This is partly accounted for by sampling the showers that are initiated in this material with a 'presampler'. The OPAL presampler is formed by a barrel of streamer tubes³ placed immediately in front of the lead glass barrel. By measuring the charged particle flux associated with converted photons a correction for ionization energy loss in the coil can be applied. Beam tests have demonstrated that at 1 GeV the resolution can be improved to 7% from 11%. The presampler also provides longitudinal shower sampling which can be used to improve electron pion separation over and above that provided by the lead glass and central detector. A factor of two improvement is expected in the ratio

$$\frac{\text{no. of } \pi \text{ identified as electrons}}{\text{no. of electrons}}$$

²The cross section of the blocks at the inner and outer radii will be slightly different.

³These are the same type of tubes used in the hadron calorimeter.

for an electron detection efficiency of 95%. The spatial resolution of around 4 mm also provides for the ability to improve the discrimination between neutral pions, which decay predominantly into two photons, and single photons. In the endcap there is roughly one radiation length of material and this region is instrumented with a presampler as well.

Immediately surrounding the coil is a barrel shaped time-of-flight scintillator (TOF) hodoscope. The 160 counters are $\sim 700\text{ cm}$ long and extend 5 cm radially and 9 cm in $r-\phi$. The TOF serves three functions: (a) it measures the velocity of the particles up to $\sim 2\text{ GeV}$ which is used for particle identification independent of the central detector dE/dx measurement (b) it provides an electromagnetic energy measurement with a resolution of $\sim 8\%$ for minimum ionizing particles and (c) it provides trigger information for the general OPAL trigger and for cosmic rays, which is useful as a veto and for calibrations of other OPAL detector components.

Hadronic calorimetry is provided in OPAL by both the electromagnetic calorimeter, which is 1.5 interaction lengths deep, and the hadronic calorimeter. The hadron calorimeter is designed to correct the total energy measurement, as made in the central detector and electromagnetic calorimeter, for energy that is carried by long lived neutral hadrons⁴ and to provide muon tracking through the calorimeter iron. The hadron calorimeter is divided into a barrel, a pair of outer endcaps and a pair of poletip sections. The 10.4 m long barrel is formed by segmenting the OPAL magnet iron yoke into $24 \times 15^\circ$ $r-\phi$ wedges. It is radially segmented into eight 10 cm thick iron plates followed by more iron (up to 20 cm in the central region) at the outer radius. The eight gaps that are formed in this way are instrumented with plastic streamer tubes with a ninth sample placed in front of the plate at the inner radius. The streamer tubes, using the basic design of E. Iarocci⁶⁴, are 3.7 m to 5.7 m long and are made in modules of four to eight. Each wedge has 1800 tubes

⁴neutrons and K_L^0 's.

that are read out with pads arranged in forty-eight towers that point towards the interaction point to measure the energy flow over the 75% of 4π that is covered by the barrel. The tubes can also be read out with strips attached along the length of the tubes which is useful for tracking muons through the calorimeter. The outer endcaps have seven plates and eight samples and also use streamer tubes. There are 192 towers pointing towards the interaction point in the outer endcaps. The poletips have ten 8 cm thick annular iron plates separated by 1 cm gaps that are instrumented with thin gap proportional chambers with pad readout arranged in 192 towers. The total solid angle coverage of the hadron calorimeter is 97% of 4π . The combined hadronic energy resolution is $130\%/\sqrt{E [GeV]}$.

An external muon identifier consisting of a barrel and endcaps, covering 70% and 25% of 4π respectively, will be installed on the outside of the hadron calorimeters. Muons are identified by their penetration through the approximately 7.7 interaction lengths of the calorimeters and by requiring that an external track matches, within the limits of multiple Coulomb scattering, a central detector muon identified track. The barrel consists of four layers of 10.5 m long drift chambers having an r - ϕ oriented drift with a width of 60 cm and point resolution of 1 mm. An end-to-end signal propagation time difference measurement provides a z measurement with a precision of a few centimetres. The endcaps are instrumented with streamer tubes of the type used in the hadron calorimeter and have a spatial resolution of ~ 1.5 mm for tracks at normal incidence.

Appendix B

Influence of Chamber Gas Properties on Vertex Detector Performance

The properties of a gas that influence its operation in a high resolution drift chamber include its primary ionization and thermalization characteristics, velocity-electric field dependency, electron diffusion, Lorentz angle, gain characteristics, and radiation hardness. The influence of each of these factors on the operation of a high resolution tracking detector is discussed.

B.1 Primary Ionization and Thermalization

The ionization of a gas by a charged particle is quantitatively understood^[65] in terms of the exchange of a virtual photon between the incident particle and atomic electron. On the macroscopic scale a discrete number of ionizing collisions occur randomly along the trajectory of the incident particle and the cross section for primary collisions depends on the details of the gas. This is important in the choice of a chamber gas because it sets the scale for the amount of information available for determining the trajectory of the incident particle but also determines how much information is lost due to the multiple scattering, which can be important when

long trajectories are measured. Because the vertex detector has a small lever arm, maximal primary ionization is desirable and can be achieved for a given gas by increasing the pressure. The number of primary electrons produced per centimetre at normal pressure and temperature has been measured in a small sample of gases useful for drift chambers and, with at least one notable exception¹, has been shown [66] to be very roughly proportional to the mean atomic number of the gas molecule:

$$n_p \sim 1.5 \times \bar{Z}.$$

If a noble gas is to be used in the chamber, for example, from a primary ionization statistics point of view argon is the lightest that is generally considered.² The primary electrons can have sufficient energy to further excite or ionize the gas. Photons and more electrons are produced until thermal equilibrium is attained. The cluster of primary plus secondary electrons is usually contained in a volume with a half radius of less than $10 - 20 \mu m$ at normal pressure and temperature. The average total energy lost per unit distance, or 'specific ionization', is described by the well known Bethe-Bloch formula [67] and the total number of electrons deposited is

$$n_T = \frac{\Delta E}{W_i}$$

where ΔE is the total energy lost and W_i is the effective average energy required to produce one electron-ion pair in the gas. The specific ionization sets the scale for the size of the signal prior to amplification and should be maximized for the vertex detector.

The distribution of energies carried off by the primary electron in a gas is approximately described by the Landau distribution which is characterized by a long high energy tail associated with the production of δ -rays. These high energy elec-

¹Xenon has nearly half as many primary electrons as predicted by the phenomenological expression.

²From an economic point of view, the heavier gases Xe and Kr are considered too expensive for large volume chambers. This leaves argon as the most commonly used noble gas in wire chambers.

trons can degrade the resolution in two ways. The long range of δ -rays³ distort the primary trajectory information and the large fluctuation in the amount of ionization distorts the pulse shape thereby degrading the timing resolution. A high resolution detector has the ability of discriminating against a δ -ray hit based on its large deviation from the measured track. Also, if the pulse heights are measured in the detector δ -ray interactions can be identified by their anomalously large pulses. Even after cutting δ -rays, residual fluctuations in the cluster sizes can introduce pulse shape distortions that degrade the resolution and must be considered as a significant intrinsic limit to detector resolution. The magnitude of the fluctuations is greater in argon than in polyatomic molecular gases and has provided motivation for moving away from argon based gases in high resolution drift chambers.

B.2 Electron Drift and Diffusion

B.2.1 Electron Drift Velocity

Townsend's[68] treatment of the physics of electron motion in an electric field described the drift velocity as:

$$v_{drift} = \frac{e\sigma}{\sqrt{2mkT}} \frac{E}{\rho} \quad (\text{B.1})$$

where σ is the momentum transfer cross section for the interaction between an electron and gas molecule which in general depends on the electric field, E , and where ρ is the gas density. Gases for which σ is roughly independent of E are referred to as 'cool' or 'slow' gases because the proportionality constant that describes the velocity dependence on the field is a mainly a function of gas temperature and density so at low fields the velocity is low.

Ideally, a gas with an electron drift velocity that is independent of the electric

³For example, a 3 keV electron in argon at normal pressure and temperature has a range of 100 μm .

field is desired as this reduces many of the systematic effects associated with the experimental operation of the cell. With such a gas the electric field need not be precisely known or constant in time for chamber operation. Interestingly enough, nature provides a class of gases, appropriate for drift chambers, that have electron drift velocities that become approximately independent of electric field over a range of relatively low fields. These gases have electron drift velocities that saturate at low electric fields as a consequence of the *Ramsauer effect*.⁴ The 'effect' is observed as a localized decrease in the cross section of the interaction between an electron and an atom as a function of electron energies.

At the cross section minimum the mean kinetic energy of the electrons increases and, because electron energies depend on the applied electric field, this heating or increase in velocity can be observed as a function of field. The resultant velocity-field dependency generally has a broad peak in the region of the Ramsauer effect. At low fields, therefore, the electrons can attain relatively high drift velocities, typically $50 \mu\text{m}/\text{ns}$, that are approximately independent of the applied electric field, or 'saturated'. Because the electrons possess higher energies under these operating conditions, these are commonly referred to as 'hot' or 'fast' gases. At higher fields, beyond the peak, the velocity is lower.

The advantages of operating with a saturated gas must be contrasted with the high demands that their high velocities place on the timing resolutions required to attain high resolution. Typically, a 1 ns timing resolution is required if a $50 \mu\text{m}$

⁴The Ramsauer effect, or more precisely the Ramsauer-Townsend effect, can occur if the incident electron wavelength approaches the dimensions of the atom or molecule with which it interacts. In the partial wave treatment, the cross section is

$$\sigma = \frac{4\pi}{k^2} \sum_{l=0}^{\infty} (2l+1) \sin^2 \delta_l.$$

With a sufficiently strong and localized attractive potential and at these low energies very few (one or two) partial waves significantly contribute to the scattering process. The details of the potential can cause the phase shifts of the few contributing partial waves to take on values close to $n\pi$ for particular incident energies thus causing the cross section to nearly vanish.

spatial resolution is to be reached. Historically, the spatial resolution demands on drift chambers have not been severe and this has resulted in the popularity of hot saturated gases. In the context of a vertex chamber, however, the advantages of operating with a saturated gas must be weighed against the demands they place on the electronics. There are other parameters that also enter into this resolution optimization process.

B.2.2 Electron Diffusion

The intrinsic spatial resolution is also influenced by the spread in arrival time of electrons caused by diffusion. The diffusion spread of a gas along a direction x can be described by a Gaussian distribution with sigma:

$$\sigma_x = \sqrt{\frac{2\varepsilon_K}{eE/\rho}} \sqrt{\frac{x}{\rho}} \quad (\text{B.2})$$

where ε_K is the 'characteristic energy' of a particular gas and is generally considered as a function of E/ρ . There are measurements with hot gases [69,70,71,45] that show that it tends to be smaller for x parallel to the field (longitudinal diffusion) than for x perpendicular to the field (transverse diffusion). ε_K is significantly lower in cool gases than in hot gases at comparable E/ρ .

B.2.3 Magnetic Field Effects

When the electrons drift in a magnetic field, $\vec{H}$, as will be the case in OPAL, they move under the influence of the Lorentz force. The magnitude of the drift velocity is modified slightly to v_m and the electrons drift at an angle, α_m (the Lorentz angle), to the electric field, $\vec{E}$. When $\vec{H}$ is perpendicular to $\vec{E}$, as in OPAL,

$$v_m = \frac{v_{drift}}{\sqrt{1 + (\omega\tau)^2}}$$

and

$$\tan \alpha_m = \omega\tau$$

where

$$\omega = \frac{eH}{m}$$

and τ is the mean time between collisions[68]. For a hot gas operated in the Ramsauer region the cross section is low and therefore the Lorentz angle is relatively high as compared with that of cool gases at the same E/ρ point. For example, in argon-ethane(50-50) at 4 bar pressure operated in an electric drift field of 3.5 kV/cm and a magnetic field of 0.4 T the Lorentz angle is approximately 20° while in CO₂-isobutane(80-20) with the same field and pressure the angle is closer to 2°.

B.3 Gas Gain

Gas amplification in wire chambers occurs when an electron drifts to within several wire radii of the anode at which point it acquires sufficient energy between collisions to ionize the gas on the next collision. After a mean distance of α^{-1} a drifting electron ionizes the gas thus releasing a second electron. The electrons released in these ionizations then themselves ionize the gas, further contributing to the generation of an avalanche of charge. In the most general treatment of this gain mechanism Townsend [68] showed that the multiplication, M , is:

$$M = \exp\left(\int_{r_{\text{cutoff}}}^{r_{\text{anode}}} \alpha(r) dr\right)$$

where the dependence on r comes from the fact that α depends on the field and the field changes near the surface of a wire.⁵ α is larger in noble gases than in polyatomic gases because, unlike single atoms, molecules may dissipate energy in a vibrational or rotation modes. As a consequence, if high gas gain is required for the chamber, voltages are minimized if a significant proportion of the gas is a noble

⁵This simple treatment is only valid up to gains of the order of 10⁴ at which point non-Townsend effects such as space charge and failure of the electrons to reach equilibrium with the field become significant [72,76].

gas. As remarked above, in typical drift chamber operating conditions most noble gases are also hot gases. Therefore in general the highest gain gases are fast gases.

As discussed in Section B.1 argon is the preferred noble gas for use in drift chambers. However, to reach gains in excess of $10^3 - 10^4$ in argon without entering a continuous discharge mode, a small proportion of a *quenching* gas must be used. Argon atoms that have been excited in the avalanche return to their ground state by emitting a UV photon. The quencher serves the role of absorbing these photons before they generate additional avalanches through the photoelectric emission of electrons from electrode surfaces. Polyatomic molecules are used as quenchers because of the presence of non-radiative states that permit efficient UV photon absorption. The commonly used quenchers include hydrocarbons, alcohols, freons and CO_2 . Good quenchers also inhibit secondary emission of electrons from the cathodes. This occurs when an ion drifts to the cathode where it is neutralized. If the number of modes for losing energy is limited, as in argon, excess energy can be emitted by removing a second electron from the metal surface and multiple, delayed avalanches are generated. In gas mixtures, ionic charge is efficiently transferred to the gas component having the lowest ionization potential.⁶ If that gas has non-radiative modes available, secondary emission is less likely. Because of this, the best quenchers are those molecules having the largest number of non-radiative excitation modes.

B.4 Pulse Formation

The charge signal generated by a single avalanche 74, is

$$Q(t) = -Q_0 \frac{C_{\text{chamber}}}{4\pi\epsilon_0} \ln(1 - t/t_0).$$

⁶This charge transfer occurs within 100-1000 ion-atomic collisions.

Q_0 is the total amount of charge in the avalanche, $C_{chamber}$ is the capacitance of the chamber (it is roughly 5.4 pF in the OPAL vertex detector) and t_0 is the characteristic time of the chamber:

$$t_0 = \frac{r_{anode} P}{2\mu E_{anode}}.$$

(P is the gas pressure and μ is the positive ion mobility in the gas.) The charge signal is differentiated with a time constant of $R_{termination}C_{chamber}$ when the anode wire is terminated with $R_{termination}$. For a short time constant relative to the $Q(t)$ pulse⁷, the current pulse is approximately:

$$i(t) = -\frac{Q_0 C_{chamber}}{4\pi\epsilon_0} \frac{1}{t_0 + t}.$$

The slow drift of the positive ions is responsible for the $1/(t_0 + t)$ tail of the pulse. This is a gas dependent time structure because of the dependence of t_0 on the positive ion mobility. This feature can be important when considering the two hit resolution of a detector.

B.5 Radiation Hardness

The means available to polyatomic molecules for dissipating the energy absorbed through their quenching action includes dissociation into simpler radicals. These can recombine into polymers that deposit on the electrodes. After exposure to a sufficiently high radiation dose (integral fluxes in excess of 10^7 per cm) the Malter effect⁸ 73 can take place at the cathodes and gain reduction can occur at the anodes.

⁷ In the case of the OPAL vertex detector with $R_{termination}=360\Omega$ the time constant is 2 ns.

⁸ A thin insulating layer is formed by the polymers on the cathode and a build up of positive charge occurs as newly formed ions drift to the cathode. If the leakage current through the insulating layer is small enough a large electrostatic field can be set up that pulls electrons from the cathode surface. The free electrons then drift to the anodes where they avalanche and generate more positive ions which, through the same mechanism, further build up the insulating layer. The result is that a current is continuously drawn from the cathodes which inhibits normal chamber operation. In some detectors, depending on the details of the gases and other materials present, the polymers have been observed to 'grow' as thin filaments from the cathodes in direction of the field lines.

Such radiation damage or 'aging' often requires cleaning or replacement of wires before the chamber can be returned to full operation. These effects can be reduced by ensuring that the cathode surface field is low enough to prevent the ions from gaining enough energy to dissociate into the radicals. Fields of 20 kV/cm are generally considered low enough to prevent this problem. Another solution is to avoid using quenchers that polymerize. In practice, the entire area of chamber radiation damage is not well understood. But it has been reported[77] that much of the aging that has been observed in chambers is associated with impurities in the quencher gases. As a consequence, this provides an incentive for using a quencher, such as CO₂, that can be produced with low impurity levels. The issues of radiation hardness have been taken into consideration in the OPAL vertex detector design in that no cathode surface field exceeds 20 kV/cm.

Appendix C

Gas Gain Measurements

The charge signal generated by an avalanche^[74] in a proportional chamber is

$$Q(t) = (\text{Gas Gain}) \times Q_0 \frac{C_{\text{chamber}}}{4\pi\epsilon_0} \ln(1 + t/t_0)$$

where

$$t_0 = \frac{r_{\text{anode}} P}{2 \times (\text{positive ion mobility}) \times E_{\text{anode}}}$$

In the prototype this signal was differentiated at each end of the chamber and the current signal was amplified and further differentiated in the current sensitive preamplifier. The gas gain was measured in the prototype using an ^{55}Fe source to provide a known amount of initial charge. Signals from the preamplifier were transmitted down a 40 m coaxial line into the amplifier on the Converter Modules. The analogue monitor output from the Converter Module amplifier was then fed into a Lecroy model 3001 multichannel analyzer (QVT) operating in the integrating (Q) mode. A voltage step into a capacitor was used to calibrate the components of the system. This was combined with a correction for the position of the source along the anode wire¹ to take into account the current division of the signal.

Having calibrated the system for an absolute gain measurement in this way, the gas gain of argon-ethane and CO_2 -isobutane were measured with ^{55}Fe at 3 bar and 2

¹The source was located at $z=-25\text{cm}$.

bar respectively. The temperature was $28 \pm 1^\circ\text{C}$ for the argon-ethane measurements and $26 \pm 1^\circ\text{C}$ for the CO_2 -isobutane measurements. The number of initial electrons produced by the ^{55}Fe is 231 in argon-ethane (50-50) and 190 in CO_2 -isobutane (80-20) for these gas pressures.

These measurements were combined with pulse height measurements of gain. The pulse height gain calibration was provided by measuring pulse heights with the prototype when it was filled with 3 bar argon(90%)- CO_2 (9%)-methane(1%). The gains of this gas under similar conditions were obtained from the gas gain measurements of Reference [75] and these were used to associate a prototype detector pulse height measurement with a gas gain.

The results are presented in Table C.1 as a function of anode surface field. A systematic error of upto 50% was assigned to the gain measurements and represents the uncertainties in the absolute calibration and wire-to-wire differences. The error on the ratio of any two gains of a particular gas listed in Table C.1 is less than 10%.

These measurements indicate that during the prototype studies the gas gain ranged between roughly 3×10^4 and 2×10^5 . It has been shown [76] that at such gains space charge effects influence the gas gain for anode wires of the size used in the vertex detector. For aging reasons it is desirable to keep the gas gain at or below the values used in these studies.

Gas	Pressure (bar)	E_{anode} (kV/cm)	Gas Gain ($\times 10^4$)
argon-ethane (50-50)	3	450	3.5 ± 1.3
		490	8.9 ± 2.2
CO ₂ -isobutane (80-20)	2	500	4.6 ± 2.2
		520	8.0 ± 4.1

Table C.1: ^{55}Fe Gas Gain Measurements in argon-ethane (50-50) and CO₂-isobutane (80-20) in the OPAL vertex prototype (anode radius = $10\mu\text{m}$). The systematic uncertainty of each measurement is quoted in the table while the error on the ratio of any two gains is less than 10%.

Appendix D

T0 Calibration Techniques

The T0 of an anode wire is defined as the time between the TDC start signal and the stop signal produced by the ionization of a track that passes through the wire. Contributions to the T0 include propagation times in the cables and electronics as well as the time associated with the collection of a sufficient number of drifting electrons in the gas to initiate a timing signal.

The calibration of the T0s have been separated into the determination of 'Global T0s' (GLOT0) and 'Relative T0s' (RT0). GLOT0 is a characteristic of a sector whereas the small differences of individual wire T0s from GLOT0 are the RT0s. This separates physically different contributions to the T0s thereby permitting separate optimization of calibration techniques. For example, GLOT0s change more frequently than RT0s because electronic drifting tends to be a sector-to-sector¹, and thus a global, phenomenon.

The RT0s account for the wire-to-wire differences in cable lengths and electronic delays. These are measured using three techniques:

1. TDC-RT0: the front edge of the raw TDC distribution.
2. PUL-RT0: use of a pulser that inputs the same pulse into a group of

¹ All wires within a sector are serviced by the same crate of readout electronics

Figure D.1: Examples of TDC distributions in the OPAL vertex prototype for (a) argon-ethane(50-50) and (b) CO₂-isobutane(80-20).

preamps.

3. TRK-RT0: use of systematic deviations of h_{T0} s from a track.

Various techniques for determining TDC-RT0s can be used. The approach taken here uses the fact that a TDC distribution of a wire with a drift space that has been uniformly illuminated with ionizing particles is proportional to the velocity vs time function. The TDC distribution is:

$$\frac{dN}{dt} = \frac{dN}{dx} \cdot \frac{dx}{dt} = C \cdot v(t)$$

Examples of TDC distributions for argon-ethane(50-50) and CO₂-isobutane(80-20) are presented in Figure D.1. If one assumes $v(t) \sim v(T0)$ in the vicinity of $T0$ then:

$$\int_0^N dN = C v(T0)(t - T0) = C_0(t - T0)$$

A line fitted to $\int_0^N dN$ vs t intersects the t -axis at $T0$. Examples of front edge of cumulative TDC distributions for argon-ethane(50-50) and CO_2 -isobutane(80-20) are presented in Figure D.2.

These TDC- $T0$ s are measured for each wire in a sector and the deviation of each TDC- $T0$ from the mean provides a measure of TDC-RT0 for each wire:

$$(TDC - RT0)_{iwire} = (TDC - T0)_{iwire} - \langle TDC - T0 \rangle_{sector}$$

The precision of this measurement is approximately $0.4 ns$ when the TDC distribution contains ~ 15 events per clock count. The great advantage of this method is that any intrinsic slope in $RT0$ vs *Wire No.* is measured for all wires in a jet cell.

PUL-TDC (pulser $T0$) is used in this detector to establish $RT0$ within groups of six wires because each calibration input to the preamp front end is only input to that number of wires. But within that group the $RT0$ s of each wire can be measured to $\pm 0.1 ns$. In the axial cells, which have 12 wires, the TDC- $RT0$ s are used to link the $T0$ s in the two groups of six wires. The pulser method is clearly the method of choice in the stereo cells, which only have six wires, because this last linking step is not required.

The determination of TRK- $RT0$ involves the measurement of the difference of the mean residuals of hits from fitted tracks on opposite sides of the anode plane.

$$\Delta_{TRK-RT0} = \frac{\langle Residual \rangle_{ndc1} - \langle Residual \rangle_{ndc2}}{2 \cdot v_d}$$

This is a method commonly used when the chamber gas has a well known saturated drift velocity, v_d . In gases with a strong field dependent drift velocity the technique is not as reliable because in general the drift velocity varies with drift distance, the side of the anode plane and from wire to wire. Another unfortunate problem with the TRK- $RT0$ s is that intrinsic slopes in $RT0$ vs *Wire No.* cannot be measured because the true slope of a track is not externally constrained. This effect, in fact, necessitates the explicit removal of any measured slope in $TRK-RT0$ vs *Wire*

Figure D.2: Examples of front edges of TDC distributions in the OPAL vertex prototype for (a) argon-ethane(50-50) and (b) CO₂-isobutane(80-20). Also included are the cumulative TDC distributions used to obtain T0s for (c) argon-ethane(50-50) and (d) CO₂-isobutane(80-20).

No. before correcting RT0. Failure to do so introduces spurious RT0 slopes that significantly degrade the calibration.

The approach taken in the prototype analysis has been to use the TDC-RT0 and PUL-RT0. The TRK-RT0 can be used to monitor fluctuations in RT0 in situations of insufficient statistics. The test beam data has been used to study these three methods and has shown consistency between them to within ± 0.4 ns. See Figure D.3

The GLOT0 measures the contribution of the delays in the system that are common to all wires in a sector. There are two chamber measurables from which GLOT0 have been extracted. The first is obtained from the front edges of the raw TDC distributions:

$$\text{TDC} - \text{GLOT0} = \langle \text{TDC} - \text{T0} \rangle_{\text{sector}}$$

This is a measure that is independent of time-to-distance relations in the anode region and all geometric variables in the chamber. The second method uses the anode crossing tracks. A three parameter linear fit (two intercepts, one slope) is made to the anode crossing tracks in which the slope of the segments on either side of the anode plane is constrained to be the same, but each segment has an associated intercept. The difference between intercepts, Δ_{ANX} , is used to correct GLOT0.

$$\Delta_{\text{ANX-GLOT0}} = \frac{\Delta_{\text{ANX}}}{2 \cdot v_d}$$

ANX-GLOT0 can be an unreliable measure of GLOT0 if not all systematics of the detector are understood. This is because it has dependencies that are unrelated to the GLOT0, such as the time-to-distance relation, and therefore has a tendency to mask significant systematic effects. As an example, the plot of $(\text{TDC-GLOT0} - \text{ANX-GLOT0})$ vs ϕ in argon-ethane(50-50), presented in Figure D.4, shows a strong dependency of ANX-GLOT0 on the ϕ of the track. This is because for this plot no

Figure D.3: Comparisons of Three Relative T0s Measurement Techniques

correction for the time-to-distance relationship ϕ dependency had been made before the Δ_{ANX} was determined.

Figure D.4: (TDC-GLOT0 - ANX-GLOT0) vs ϕ

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