The Time Projection Chamber of the HARP Experiment

Agnes Lundborg
Supervisor: Piero Zucchelli

April 2002
Abstract

The hadron production experiment HARP aims to measure hadron collision cross sections with a 2-15 GeV particle beam and several targets. This energy regime is in a borderline zone between the low energy region dominated by resonance formation and the high energy domain where perturbative Quantum Chromo Dynamics is applicable. The emphasis of this master thesis is put on the HARP central tracker, the Time Projection Chamber (TPC).

In the thesis work, Finite Element Method computations of the electric field in critical regions of the TPC have been performed to provide design input concerning the electrostatic configuration of the field cages and of the wire chamber.

A first step in the chain of reconstruction of the information produced by the detector is the equalisation and monitoring of \(~4000\) analogue signals. An algorithm which processes the raw digitized signals, filters out electronics noise and extracts the pad gain from signal distributions has been produced and analyzed for this purpose. The algorithm has been verified with independent calibration procedures and is now applied in the HARP reconstruction software. The thesis is concluded with a first glance at the reconstructed physics data from the HARP Time Projection Chamber.
Contents

1 Introduction 7
  1.1 The HARP experiment .................................... 7
  1.2 Physics motivation ........................................ 7
    1.2.1 Monte Carlo in low energy regimes .................. 8
    1.2.2 Atmospheric neutrino distribution .................. 8
    1.2.3 Neutrino fluxes in K2K and MiniBooNE .......... 8
  1.3 The Neutrino Factory ..................................... 8
  1.4 Master thesis project .................................... 10

2 Hadronic interactions 11
  2.1 The Standard Model ...................................... 11
  2.2 Quantum Chromo Dynamics ................................ 13
  2.3 Hadron hadron interactions .............................. 13
    2.3.1 Resonance formation ................................. 15
    2.3.2 Wave optical parameterisation of hadron scattering .. 16
    2.3.3 Black disk model ..................................... 17
    2.3.4 Meson exchange models ................................ 18
    2.3.5 Mandelstam variables ................................ 19

3 Principles of drift chambers 21
  3.1 Ionization from an energetic particle traversing a gas .... 21
    3.1.1 The Bethe-Bloch formula .............................. 22
    3.1.2 Primary and secondary ionization .................... 23
    3.1.3 Differential cross section ........................... 24
    3.1.4 Cluster size distribution ............................ 25
    3.1.5 The Landau distribution .............................. 25
    3.1.6 Energy transfer cut-off ............................... 26
  3.2 Amplification on the sense wires .......................... 27
    3.2.1 Townsend coefficient ................................. 28
    3.2.2 Gain distributions .................................... 29
  3.3 Creation of the signal on the pad plane .................... 31
4 Experimental setup
4.1 Beam .................................................. 33
4.2 Trigger .................................................. 35
4.3 Target .................................................. 37
4.4 Resistive Plate Chambers .............................. 38
4.5 NOMAD drift chambers .............................. 39
4.6 Cherenkov detector .................................... 40
4.7 Time-of-flight wall .................................... 41
4.8 Electron and muon identifiers ...................... 41
4.9 Time Projection Chamber ............................. 42
   4.9.1 Field cage ........................................ 42
   4.9.2 TPC gas choice .................................... 44
   4.9.3 TPC Chamber ...................................... 46
4.10 Signal shape in the TPC ............................. 50
4.11 Calibration systems of the TPC .................... 50
   4.11.1 Cosmic ray calibration .......................... 50
   4.11.2 Laser calibration ............................... 51
   4.11.3 Krypton calibration ................................ 52

5 Simulations of the Time Projection Chamber ....... 55
5.1 Simulation procedure .................................. 55
   5.1.1 The Quadratic Finite Elements Method ........ 56
   5.1.2 Garfield .......................................... 60
5.2 Strip structure ....................................... 60
   5.2.1 Simulation geometry ............................. 61
   5.2.2 E×B distortions close to the field cage ........ 62
   5.2.3 Distortions in time and position ................ 64
5.3 Sense wire support ................................... 64
   5.3.1 Straight angle approximation ................... 64
   5.3.2 Sense wires at a 60 degree angle against the spokes ... 69
   5.3.3 Hexagonal structure with HV supply line ........ 72
   5.3.4 Expected gain losses close to the rods .......... 75
   5.3.5 Sense wire holders design ....................... 77
   5.3.6 Outer wheel ....................................... 77
5.4 Complete wire support structure .................. 80
   5.4.1 Dielectric spoke .................................. 80
   5.4.2 Dielectric spoke with a guard ring ............. 82
   5.4.3 Support with metal inserts ...................... 82

6 Gain equalisation of the HARP TPC ................. 83
6.1 Data choice .......................................... 84
6.2 Gain measure ........................................ 84
6.3 Equalisation from physics trigger raw data ........ 85
   6.3.1 Monte Carlo simulation of the method .......... 86
6.3.2 Noise rejection ........................................ 88
6.3.3 Validity of the method .................................. 88
6.4 Equalisation using filtered data .......................... 89
  6.4.1 Equalisation using cosmic ray data ............... 90
  6.4.2 Quality and stability ................................ 92
  6.4.3 Equalisation map ................................... 94
  6.4.4 Sources of gain variations ......................... 94
6.5 Comparison with krypton calibration .................... 97
6.6 Noisy pads ............................................. 98

7 Reconstruction of particle trajectories in the HARP TPC 101
  7.1 The TPC reconstruction package ........................ 101
    7.1.1 Clustering ........................................ 102
    7.1.2 Pattern recognition ............................... 104
    7.1.3 Helical fit ...................................... 105
  7.2 Cosmic rays ........................................... 106
    7.2.1 Trigger .......................................... 106
    7.2.2 Angular distribution ............................. 107
  7.3 Proton collisions on Ta at 3 GeV .................... 109

Conclusions ................................................. 111

A Cosmic rays .................................................. 113
  A.1 Cosmic ray distribution in the TPC polar coordinate system 115

B Neutrino physics ............................................ 117
  B.1 Solar neutrinos ...................................... 117
  B.2 Atmospheric neutrinos ................................ 118
  B.3 Coupling between oscillations and masses ............ 120

C HARP Software package .................................... 123
  C.1 The HARP Software environment ...................... 123
  C.2 GAUDI ............................................. 124
  C.3 Equalisation code ................................... 124
Chapter 1

Introduction

1.1 The HARP experiment

The Hadron Production experiment HARP aims to determine total and differential cross sections for hadron production to an accuracy of 2%. HARP is a fixed target experiment, with proton and pion projectiles with momentum from 2 GeV to 15 GeV impinging on thin and thick targets over a large range of atomic numbers. Measurements of scattering on a large range of solid targets have been performed during the fall of 2001. Analysis of these data is in progress. During an additional data taking period in 2002, these data will be complemented with cryogenic targets and additional solid targets.

1.2 Physics motivation

Previous measurements in the energy regime of the HARP experiment, are generally old, have an uncertainty of 15% in the absolute normalization and neither cover a large energy region nor a large range of targets. Moreover, in this energy regime both QCD perturbative calculations and resonance production models are difficult to apply. Predictions are therefore extrapolations from lower or higher energies which depend critically on the kind of parametrisation used (discrepancies can be as large as 100%). A better knowledge of hadron reactions in the non perturbative energy regime would be useful in many different contexts: to understand and develop nonperturbative models, to give input to simulation packages, to understand the atmospheric neutrino distribution, to measure and predict neutrino yield from conventional neutrino beams and for optimization of the neutrino factory target and focusing system.[13]
1.2.1 Monte Carlo in low energy regimes

Precise values of cross sections on targets across the periodic table would provide input data for hadron generators in Monte Carlo packages and thereby help in understanding and predicting particle production for experiments in the future.

1.2.2 Atmospheric neutrino distribution

The determination of the flux of atmospheric neutrinos at energies below $E_\nu < 10$ GeV, is presently afflicted by a 30% uncertainty in the absolute flux and a 7% uncertainty in the flavour composition. Better understanding of the neutrino flux and flavour composition is needed for a refined interpretation of atmospheric neutrino experiments. One such experiment is the SuperKamiokande (SK) experiment which has recently made the important claim of discovery of neutrino masses. With recent precise measurements on the primary cosmic ray flux, the major source of uncertainty in the SK evidence is the lack of knowledge on hadronic interactions in the regime of low energy transfer. Present calculations are generally based on measurements from single-arm hadron experiments, carried out in the seventies with 15% uncertainties in the absolute normalisation and without any coverage of lower energy particles. The HARP measurements on protons and pions colliding with oxygen, hydrogen and nitrogen will clarify this important result.[13]

1.2.3 Neutrino fluxes in K2K and MiniBooNE

Neutrino beams are generally created from proton collisions on a target, pion focusing and decay. Two such experiments are the K2K experiment on the KEK proton-synchrotron and the MiniBooNE experiment at the low-energy booster at Fermilab. In MiniBooNE a low energy proton (8 GeV/c) collides with a beryllium target, giving a beam of $\nu_\mu$ from $\pi^+$-decay. The aim is to study $\nu_\mu \rightarrow \nu_e$ oscillations [46]. The K2K project uses neutrinos from the decay of pions and kaons produced in collisions between 12 GeV protons and an aluminium target. To conduct disappearance and appearance experiments, the original composition of the beam must be known to a high precision. A step towards this knowledge is to understand the original pion production step. HARP measures the pion and kaon yield at the same energy using target replicas from the two experiments.

1.3 The Neutrino Factory

The recent neutrino oscillation claims are based on the measurement of solar and atmospheric neutrinos, with a limited knowledge of the initial neutrino
Figure 1.1: A conceptual layout of the proposed Neutrino Factory at CERN. It involves a proton accelerator, a target, a focusing system, reaccelerating systems and a muon storage ring with two straight sections where the muons decay to an electron (or positron) and two neutrinos giving high intensity neutrino beams directed towards two detectors at a distance.

flux and composition. Another possibility is to produce a neutrino beam in a laboratory. By letting a proton beam impinge on a target, pion, kaons and muons are produced, which decay to neutrinos. Such beams have been used in experiments such as LSND, K2K, KARMEN, MiniBooNE and the CERN based experiments CHORUS and NOMAD.

A new ambitious program along these lines has been investigated at CERN since 1999: the Neutrino Factory. It involves a proton accelerator, a target, a focusing system, reaccelerating systems and a muon storage ring. The storage ring would be equipped with two straight sections where the muons decay to an electron (or positron) and two neutrinos, giving high intensity neutrino beams directed towards two detectors at large distances. It is foreseen to use a Super Conducting Proton Linac (SPL) for proton acceleration. The SPL, to be built from spare parts from the large electron positron collider (LEP), would be capable of producing a 4 MW proton beam at 2.2 GeV/c. There are high demands put on the target: it should give a large pion flux and it must be able to stand the mechanical and thermal shock of the high intensity beam. The presently considered solution is a liquid mercury jet with a thickness of two interaction lengths. The pions
produced at the target and the muons from pion decay would then undergo ionization cooling: a focusing stage where their transverse momentum is reduced. The next step would be an acceleration stage increasing the longitudinal momentum up to 50 GeV/c before the muons would be allowed to enter a storage ring with two straight sections. In the storage ring the muons will decay giving high intensity neutrino beams according to

\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]
\[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]

The beam would be directed towards detectors at large distances, one in Italy at a distance of 732 km and one in Norway or Spain at a distance of about 3000 km. A schematic layout of the neutrino factory is presented in fig. 1.1.

High precision knowledge of the pions momentum and yields is required to optimize the target, the pion capture, the ionization cooling and the phase rotation. This knowledge will be provided by HARP.

### 1.4 Master thesis project

The HARP experiment was approved in March 2000. During the year 2000 design and construction proceeded in parallel. Many details that could not be tested with prototypes due to the tight time schedule were instead simulated. The first task of this master thesis was the electrostatic design of the HARP time projection chamber (TPC) field-cage, wires and wire support structures. The design goal was to minimise drift distortions, charge-up on dielectric surfaces and electrostatic risks, such as sparks or corona formation, while keeping a high and constant gain on the pad plane. The simulations, performed within the framework of the CERN summer student program (2000), provided input to the detector design. In 2001, data taking, software development and calibration (understanding the detector behaviour) were the main issues. The part of this process which is in particular a task of this thesis is the equalisation of the TPC pad plane and analysis of the gains and distortions with comparison with the expectation from simulation. The last part of the thesis describes the current status of the event analysis and reconstruction. Although preliminary, it is a first step towards the experiment goals of HARP.
Chapter 2

Hadronic interactions

2.1 The Standard Model

The standard model of particle physics describes the smallest known constituents of matter and their interactions. It is the best validated and most commonly used model within particle physics, and has successfully anticipated and explained many observations to a great precision [1].

According to the standard model, matter is built up from point-like building blocks called fermions. The fermions are grouped into three generations which are tabulated in figure 2.1. Each generation includes a negatively charged lepton such as the electron, a massless neutrino and two quarks with fractional electric charges, \( \pm \frac{2}{3} \) and \( \pm \frac{1}{3} \). Each generation also has an antimatter counterpart with the same masses but opposite charges.

The standard model describes forces as exchange of force field quanta. The force field quanta, called gauge bosons, are listed in figure 2.2. There are four fundamental forces: gravity, the strong force, the weak force and the electromagnetic force. At high energies, the electromagnetic and the weak force are joined into the electro-weak force. The electromagnetic force, mediated by massless photons, acts between electrically charged particles. The weak force affects all known particles, it is mediated by three massive exchange particles: the charged \( W^+ \) and \( W^- \)-bosons and the neutral \( Z^0 \)-boson. The strong force, which holds quarks together in hadrons\(^1\), is mediated by eight different massless gluons.

The interaction rate depends critically on the intrinsic strength of the force itself, expressed through a coupling constant \( \alpha \), different for each force. The value of the coupling constant depends on the energy exchanged between the interacting particles. Approximate values are listed in table 2.1 [3]. A reaction can always proceed in many different ways: through the exchange of one or multiple bosons creating intermediate fermion-antifermion pairs on

\(^1\)A hadron is a particle that consists of quarks, there are two kinds of hadrons: baryons with three quarks and mesons with one quark and one antiquark
**Fermions**

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ electron neutrino</td>
<td>$&lt;1 \times 10^{-8}$</td>
<td>0</td>
</tr>
<tr>
<td>$e$ electron</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\mu$ muon neutrino</td>
<td>$&lt;0.002$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$ muon</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\tau$ tau neutrino</td>
<td>$&lt;0.02$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ tau</td>
<td>1.7771</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Quarks**

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ down</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$ charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$ strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$ top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ bottom</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

Figure 2.1: Within the standard model all matter consists of point-like particles called fermions. There are three generations of fermions, with each generation consisting of two quarks and two leptons. Each of the fermions has an antiparticle reflection, not shown in the table.

**Bosons**

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W^-$</td>
<td>80.4</td>
<td>-1</td>
</tr>
<tr>
<td>$W^+$</td>
<td>80.4</td>
<td>+1</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>91.187</td>
<td>0</td>
</tr>
</tbody>
</table>

**Strong (color) bosons**

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g$ gluon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2.2: The forces between the fermions are mediated by exchange of field quanta, called bosons. The electromagnetic force is mediated by massless photons acting between charged particles. The vector bosons $W^+$, $W^-$, and $Z^0$ can act between any two particles, but very weakly. This interaction is called the weak force. The strong force, holding quarks together in hadrons, is mediated by eight different massless gluons.
their way. For each extra emission/absorption, the interaction rate of the process is multiplied by a factor $\alpha^2$. To get a total reaction rate, all reaction routes should, in principle, be taken into account. In the electroweak theory, where the coupling is weak, $\alpha_{em} = 1/137 << 1$, this complication can be solved through perturbation theory. Perturbation theory treats higher order quantum exchange as small corrections to single quantum exchange.

### 2.2 Quantum Chromo Dynamics

Quantum chromo dynamics (QCD) is the part of the standard model dealing with interactions between quarks. QCD describes a baryon as a combination of three quarks with different colour charges, glued together with colour forces. Mesons are described as combinations of one coloured quark and one anti-coloured antiquark. The force between the quarks is mediated by eight different massless and electrically neutral gluons carrying a combination of colour charge and colour anti-charge. The colour of the gluons themselves, allow them to interact with colour forces as well. This self-interacting property of gluons make the force between colour charged objects increase with distance, like for a stretched string. If the energy required to stretch the string is larger than the mass of a quark-antiquark pair, the string snaps and two mesons are produced from the original one. In practise this leads to confinement of quarks within colourless baryons or mesons (fig. 2.3).

The behaviour of the strong force, described above, is parametrised by the running coupling constant $\alpha_{strong}$. The coupling constant depends on the energy scale in which the measurement is made, as shown in figure 2.4 [2]. It is the very strong coupling at low energies, that give quark confinement within colourless hadrons. The typical radius of a hadron is $\sim 1$ fm, giving an energy scale of about 200 MeV for the interactions within the hadron.

### 2.3 Hadron hadron interactions

Forces between colourless hadrons can be considered as residuals of colour interactions, analogous to when neutral atoms interact through higher electric moments. As argued above, it is impossible to calculate two-quark interactions from first principles (QCD) at low momentum $q \leq 1$ GeV, where the HARP experiment operates. It is even harder to find analytic solutions to
Figure 2.3: Quantum chromo dynamics (QCD) describes baryons, like the proton in the picture, as composed of three coloured quarks held together by gluon exchange. The self-interacting property of gluons makes the force between colour charged objects increase with distance like a stretched string. When the string is stretched too much it snaps and a new quark-antiquark pair is created. This behaviour leads to confinement of quarks within colourless hadrons or mesons.

Figure 2.4: The coupling constant for the strong interaction depends on the momentum transfer $\mu = \sqrt{q^2}$ (this is the $q^2 = -t$ of formula (2.9)) between the interacting parts. At very high momentum transfers the coupling constant becomes smaller than 0.3 which is small enough for perturbation theory calculations. At lower energies the coupling increases and perturbation methods are no longer reliable [2].
many body interactions, as those between all the quarks of hadrons. Instead, there are approximate models, applicable in different situations and energy regimes. These models are able to describe or parameterise interactions, but have no predictive power.

### 2.3.1 Resonance formation

A resonance is an unstable intermediate state in a reaction. It manifests itself as an increase of the reaction probability at and around a given centre-of-mass energy, \( E_R \) with a width \( \Gamma \). This increase has the Breit-Wigner shape seen in figure 2.5. It is expressed as,

\[
\sigma_{\text{elastic}}(E_{\text{cms}}) = 4\pi\lambda^2(2l + 1) \frac{\Gamma^2/4}{(E_R - E_{\text{cms}})^2 + \Gamma^2/4}
\]  

(2.1)

where \( E_{\text{cms}} \) is the center-of-mass energy of the interacting particles, \( \lambda \) is the de Broglie wavelength divided by \( 2\pi \) and \( l \) is the angular momentum quantum number of the system.

Additional to the energy and the lifetime (\( \tau = \hbar/\Gamma \)), the resonance has all properties of an unstable particle, such as for instance a parity, a spin, a charge, an isospin and preferred decay channels. For inelastic resonances, where the resonance can decay into different final states, the decay probability into a given final state is expressed through the partial decay width, \( \Gamma_f \), and the total width of the resonance is the sum over the partial decay widths,
\[ \Gamma_{\text{total}} = \sum_f \Gamma_f. \]

By time reversal symmetry, a given resonance, which can decay to different final states, can also be produced from different initial states, with the same coupling. This way, the same inelastic resonance can be involved in different reactions with the same quantum numbers. Taking this, and spin, into account a more general Breit Wigner formula, for the case \( a + b \to c + d \), is obtained

\[
\sigma(E_{\text{cms}}) = 4\pi\lambda^2 \frac{2J + 1}{\sqrt{(2s_a + 1)(2s_b + 1)} \sqrt{(2s_c + 1)(2s_d + 1)}} \frac{\Gamma_{\text{el}} \Gamma_{\text{el}}/4}{(E_R - E_{\text{cms}})^2 + \Gamma^2/4}
\]

where \( s_a \) and \( s_b \) are the spins of the two incoming particles, and \( s_c \) and \( s_d \) those of the two outgoing particles. For a more comprehensive treatment, the reader is referred to [1].

### 2.3.2 Wave optical parameterisation of hadron scattering

The shape and magnitude of differential cross sections in hadron scattering experiments, \( d\sigma(\theta, \phi, E)/d\Omega \), at center-of-mass energies of the order of \( E_{\text{cms}} \sim 1 \text{ GeV} \), generally show typical structures, as is shown in figure 2.6 for the case of pion-proton collisions. The method of partial wave scattering, adopted from nuclear physics, parameterises this low energy behaviour, by decomposing the scattering distribution, into spherical wave components. The amplitude and the phase of the wave components is determined by fits.
to data.

The unperturbed particle flux is described as a plane wave, $\Psi_i$, which can also be viewed as a superposition of spherical waves with all angular momenta, $l$. The scattering center affects the spherical wave components, by changing their phase by $2\delta_l(E_{\text{cms}})$ and their amplitude by a factor of $\eta_l(E_{\text{cms}})$. The scattered wave is found from the difference between the incoming plane wave, $\Psi_i$, and the phase shifted and amplitude modulated total wave,

$$\Psi_{\text{scatt.}} = \frac{e^{ikr}}{kr} \sum_l (2l + 1) \frac{\eta_l e^{2i\delta_l} - 1}{2i} P_l(\cos \theta) = \frac{e^{ikr}}{r} F(\theta) \quad (2.3)$$

where $k$ is the wave number of the incoming plane wave, $l$ is the angular momentum quantum number, $P_l(\cos \theta)$ are the Legendre polynomials and $F(\theta)$ is the scattering amplitude in the the centre-of-momentum frame [1]. From this treatment, the total cross section, and the inelastic component of the total cross section are found as:

$$\sigma_{\text{total}} = 2\pi \lambda^2 \sum_l (2l + 1)(1 - \eta_l \cos 2\delta_l) \quad (2.4)$$

$$\sigma_{\text{reaction}} = \pi \lambda^2 \sum_l (2l + 1)(1 - |\eta_l|^2) \quad (2.5)$$

where $\lambda$ is the de Broglie wavelength divided by $2\pi$. From the formula 2.4, we note that each wave component will undergo a maximum when its phase change $2\delta_l = \pi$. This is how a resonance is identified within the wave optical method. A simple comparison between the formulae for the total cross section, equation 2.4, and the scattering amplitude, equation (2.3), gives the optical theorem,

$$\sigma_{\text{total}} = \frac{4\pi I m F(0)}{k} \quad (2.6)$$

2.3.3 Black disk model

At higher energies, resonance and threshold effects are less pronounced and, in a large range of energies, the total cross section of many hadronic scattering interactions is almost constant, as shown in figure 2.7. A constant cross section is obtained from scattering on a totally absorbing disk with a fixed radius. The radius $R$ of the disk, would for hadron interactions have about the same size as a hadron i.e. $\sim 1$ fm. Incoming particles, with an impact parameter inside the disk $b = l/p < R$ would be absorbed (react inelastically), leaving a diffraction shadow behind the disk. The diffraction shadow is, at small angles, well approximated by

$$\frac{d\sigma_{\text{elastic}}}{dq^2} = \pi R^4 \left| \frac{J_1(Rq)}{Rq} \right|^2 \quad (2.7)$$
where \( J_i(Rq) \) is the first order Bessel function, with the scattering angle expressed as a momentum transfer \( q \), \( q = 2k \sin \theta/\gamma \), where \( k \) is the wave number of the particle. This very simple model does actually have some predicting power. It can, for example, coarsely predict the diffraction minimum for pion-proton collisions seen in figure 2.8.

### 2.3.4 Meson exchange models

Residual colour interactions can be explained by particle exchange, by letting virtual mesons mediate the force, in a way similar to photon exchange (figure 2.9). From the uncertainty principle, the allowed life time of a virtual particle depends on its borrowed energy \( \tau \leq h/\Delta E \). Consequently, the lightest mesons have the longest lifetime and the largest range. The pion dominates the exchange process at distances larger than 1 fm (\( \tau \sim 1 \text{ fm/c} \).
Figure 2.9: Residual colour interactions can be explained through particle exchange, similar to photon exchange in electromagnetic interactions. This can most easily be seen as simplifying the many contributions from exchange of combination of gluons and quark-antiquark pairs, into the exchange of a single meson.

For closer encounters, other meson exchange diagrams also become important, and more and more mesons have to be considered as the momentum exchange becomes even larger. Conservation laws tell us that quantum numbers must be preserved, both at emission and absorption of real and virtual particles. In principle, all combinations of quark-antiquark and gluon exchanges, obeying the conservation laws should be possible. Describing the exchanged particle not as any given meson, but as characterised only by its quantum numbers would include all these combinations. It is a more powerful description than meson exchange, since now interactions can proceed even in cases when, within the standard model, no particle with the proper quantum numbers exists. What is referred to as a meson exchange, is therefore, at a deeper level, a single particle approximation to many complicated exchanges of quark-antiquark pairs and gluons [4].

2.3.5 Mandelstam variables

In a collision process

\[ a(\vec{p}_a) + b(\vec{p}_b) \rightarrow c(\vec{p}_c) + d(\vec{p}_d) \]  

(2.8)
an apart from the invariant masses of each particle, two independent Lorentz-invariant quantities can be formed from the four-momenta of the particles namely:

\[ s = -(p_a + p_b)^2 = -(p_c + p_d)^2 = E^2 \]
\[ t = -(p_a - p_c)^2 = -(p_b - p_d)^2 = -q^2 \]  

(2.9)
The variables \( s \) and \( t \) are called Mandelstam variables and are used to characterise reactions. In low energy processes, such as those described above, intermediate state resonances, formed from the initial particles, dominate the interaction. These states are characterised by the centre-of-mass energy of the system \( s \), one says that the reaction proceeds through the \( s \)-channel. At higher energies (i.e. above 10 GeV) there is a smoother variation of the
cross section, which is more easily described through exchange of force mediating particles. The reaction is then better characterised by the momentum exchange \( q \) and proceeds in the t-channel.[1]

To the reaction (2.8) there is a crossed reaction defined as

\[
a(p_a) + d(-p_d) \rightarrow c(-p_c) + b(p_b)
\]  

(2.10)

The definition of the Mandelstam variables gives that the original momentum transfer \( t \) equals the invariant energy \( s_{\text{crossed}} \) of the \( a\bar{d} \) system \( (t = s_{\text{crossed}}) \), and \( s = t_{\text{crossed}} \). The principle of crossing symmetry states that the original and the crossed reaction are described with the same amplitude. This means that exchange particles in the original interaction correspond to resonances in the crossed interaction and vice versa.

This principle is one of the corner stones of the so called Regge theory. In the Regge-pole model, angular momentum is treated as a continuous complex variable \( \alpha \), which is found from the best fit to data. Whenever \( \text{Re}(\alpha) = l \) acquire integer values, there is a pole in the reaction amplitude corresponding to either a bound state or a resonance. The crossing symmetry creates a link between exchange particles and resonances, which makes it possible to describe both reactions within one Regge pole parametrisation. For details the reader is referred to [1] or [4].
Chapter 3

Principles of drift chambers

A drift chamber is an apparatus for measuring the space coordinates of the trajectory of an energetic particle. This is achieved through detection of ionization electrons, produced in collisions between the charged particle and the chamber gas. One example of a drift chamber is a time projection chamber, more often referred to as a TPC, which is divided into two parts: the drift space and the chamber. The ionization electrons from the track will be pulled by a constant electric field through the drift space towards the chamber. In the chamber the electrons are multiplied via avalanche processes, and the arrival time and position are measured on sensitive electrodes. This information is used to determine the coordinates of the charged particle tracks, their momentum and, through the energy loss per unit distance $dE/dx$, their identity. In this chapter the ionization along the particle track, the amplification avalanche and the signal induction on the read out electrodes will be discussed.

3.1 Ionization from an energetic particle traversing a gas

An energetic charged particle transfers energy to the medium in which it travels by collisions. A fraction of the energy loss is translated into ionization, which can be detected. The process, from the collision between the charged particle and the gas molecules to the electrons in equilibrium drifting towards the chamber, involves many steps. In this section we will start by describing the mean ionization, expressed in the Bethe-Bloch formula and continue with describing the process in some detail. This involves the difference between primary and secondary ionization, the differential cross section for energy transfers in primary collisions and the cluster size distribution which expresses the number of electrons per primary encounter, all summarized in the distribution of the number of electrons per unit track length, the Landau distribution. Finally we conclude with some remarks
Figure 3.1: The mean rate of energy loss for various charged particles at different momenta [2]. The dots show the observed mean energy and the lines the Bethe-Bloch curve for different particle species. Note however that electrons in this energy regime have the main energy loss by radiation and therefore do not follow the Bethe-Bloch shape.

about high energy cut-offs which can be introduced to make the theoretical distributions more physical.

3.1.1 The Bethe-Bloch formula

A charged particle moving in a gas loses small amounts of kinetic energy due to electromagnetic interactions with the gas molecules. The energy losses can be well described by the Bethe-Bloch formula, if a measurement is made on a large enough scale. The Bethe-Bloch formula expresses the mean ionization density as

\[
< \frac{dE}{dx} > = \frac{4\pi N_0 z^2 e^4 Z}{m v^2} A \left[ n \left( \frac{2mv^2}{I(1 - \beta^2)} - \beta^2 \right) \right]
\]  (3.1)

Here \( I \) is a gas specific effective ionization potential, \( N_0 \) is the Avogadro number, \( z e \) is the particle charge, \( Z \) and \( A \) the gas atomic and mass numbers and \( \beta = v/c \) the velocity of the particle normalised to the speed of light. The \( x \) in the formula is the path length times the density of the medium. Typical values for the energy losses are of the order of 1.5 MeVcm²g⁻¹ which corresponds to 2.6 keV/cm in argon gas. These values are much smaller than the particle kinetic energy, which typically is in the regime 10 MeV to 10
GeV. For a given momentum, the Bethe-Bloch formula gives different predictions for different particles, as shown in figure 3.1. Comparison between measured energy losses and the Bethe-Bloch prediction for different particles is used for particle identification in the so called $dE/dx$-method. We note that the Bethe-Bloch formula is not valid for electrons, which loose energy mainly by radiation in this regime.

The Bethe-Bloch formula gives the mean energy loss along a track. However, in practice there will always be fluctuations about the mean on any given track length. The distribution of ionization on a track length around the mean value is given by the so called the Landau distribution, to be discussed later in this chapter. The Bethe-Bloch formula includes all high-energy transfers kinematically possible, whereas in real life there are effective cut-offs, also to be mentioned later. The cut-offs can be corrected for, giving a chamber dependent modified Bethe-Bloch formula (see [7] for a derivation of the complete expression).

### 3.1.2 Primary and secondary ionization

The number of primary collisions between the charged particle and the gas, along a length $L$ of the charged particle path, is characterised by the mean free flight path $\lambda$. With a constant interaction probability over a path length, $P = ds/\lambda$, the number of collisions is expressed by a simple Poisson distribution, giving the probability of having $k$ collisions on the flight path $L$:

$$P(L/\lambda, k) = \frac{(L/\lambda)^k}{k!} \exp(-L/\lambda)$$

(3.2)

The Poisson distributions, for a set of values $\lambda' = L/\lambda$ is shown in fig. 3.2. The primary collisions treated in this context are electromagnetic, proceeding through excitation of atoms and nuclei or photo emission of electrons. A complete quantum mechanical calculation would involve transition amplitudes of all possible atomic states. This is too complicated to be performed analytically.

The energy distribution of the primary electrons depends on the identity of the particle and the chamber gas. Generally, it has a shape roughly of the form $N(E) \sim dE/E^2$, where the high energy tail is dominated by the so called $\delta$-rays. Delta rays are historically defined as being the energetic electrons, able to give distinguishable tracks in the drift chamber. Clearly, this definition of delta rays is detector dependent.

The final population of electrons is about four times larger than the number of primary electrons. This is because other secondary interactions occur between energetic ionization electrons and the chamber gas. Not all the energy lost by the particle ($dE/dx$) goes into ionizing molecules. The actual ratio between energy lost and energy used for ionization is a density dependent gas characteristic, which for sufficiently high energies (keV elec-
trons and MeV alpha particles) happens to be independent of the particle energy. It is expressed as an effective ionization energy denoted by $W$. The value of $W$ for a particular gas mixture can be increased by adding a small amount of a gas with a low ionization potential. For further details please consult [7].

### 3.1.3 Differential cross section

For energy transfers much higher than electron binding energies ($E \gg E_{k,shell}$), electrons bound in atoms behave as free particles and the differential cross section $d\sigma/dE$ for primary electrons approximately becomes that of Rutherford scattering

$$
\frac{d\sigma}{dE} = \frac{2\pi\rho^2}{\beta^2} \frac{mc^2}{E^2}
$$

where $\rho = e^2/mc^2$ is the classical electron radius and $m$ is the mass of the energetic particle. The Rutherford cross section has a long high energy tail ($\sim 1/E^2$). A problem with the Rutherford approximation of free electrons, is that, although the total cross section $\sigma_{tot}$ is finite, the mean transferred energy per collision has a logarithmic divergence,

$$
E_{\text{mean}} = \frac{\int EN \frac{d\sigma}{dE}dE}{\int N \frac{d\sigma}{dE}dE} = \int \frac{dE}{E} \propto \ln E
$$
3.1.4 Cluster size distribution

The distribution of the number of electrons, created with each primary encounter, is referred to as the cluster size distribution, since these electrons are often found as a cluster in space. The cluster size distribution summarizes all details of all possible ionization mechanisms but is very complicated to give it a valid analytical formula. Monte Carlo simulation has still not quite managed to reproduce the experimental cluster size distribution, but simulations and measurements are slowly converging towards a consensus [7].

From the cluster size distribution, the number of electrons produced on a given track length can be obtained simply by summing up all the clusters given from each primary encounter along the track. This is done with Monte Carlo methods using tabulated values of cluster sizes. The procedure gives a distribution with a peak that defines the most probable number of electrons, and a full width at half maximum. A weakness of the assumptions is the high energy divergencies of the mean and the RMS. Those can be defined only if upper cut-offs on energy transfers in primary collisions are introduced.

3.1.5 The Landau distribution

An approximation of the number of electrons on a given track length can be found through the energy loss distribution, $F(x, \Delta E)$, on a given track length $x$ and with a given energy loss $\Delta E$, divided by the average energy required for ionization, $W$. This was done by Landau in 1944 [9]. The Landau treatment results in a general expression, which can be further evaluated by assuming the differential cross section to have the Rutherford form. The Landau distribution is a one dimensional function of the variable $\lambda$ expressed through the most probable energy loss $\Delta E_{mp}$ and an energy loss scaling factor $\xi$, $\lambda = \frac{\Delta E - \Delta E_{mp}}{\xi}$. Both the $\Delta E_{mp}$ and the $\xi$ can, in principle, be found analytically from known parameters of the problem. They are, however, normally obtained from the best fit to the measured electron distribution. The shape of the Landau curve is shown in figure 3.3. A simulated truncated distribution for the HARP gas mixture is shown in figure 3.4 [24]. The high energy divergencies of the Rutherford differential cross section, gives divergencies also in the Landau prediction of the mean number of electrons and the RMS of the distribution. In order to make the distribution more physical a cut-off is usually introduced. The Landau expression is valid for thin layers, in the HARP case the pad length $x \sim 1$ cm is considered as a thin layer. As the layer thickness increases, the tail of the distribution becomes less and less pronounced. Finally, for very thick layers it approaches a Gaussian as is given from the central limit theorem. The problem of medium thick layers (in between Landau and Gaussian distributions) has been investigated by Vavilov, who derived a distribution characterised by
the variable \( k = \frac{\Delta E_{\text{mean}}}{\Delta E_{\text{max}}} \), where \( \Delta E_{\text{max}} \) is the maximum kinematically allowed energy loss in a collision and \( \Delta E_{\text{mean}} \) is the mean energy loss over the layer. The Vavilov distribution is well approximated by the Landau distribution at values of \( \frac{\Delta E_{\text{mean}}}{\Delta E_{\text{max}}} \) < 0.01 and by the Gaussian for \( \frac{\Delta E_{\text{mean}}}{\Delta E_{\text{max}}} > 10 \) \[8\].

### 3.1.6 Energy transfer cut-off

The high energy divergencies of the mean energy transfer and the mean number of electrons is a problem with the distributions treated above. Fortunately, there is a natural solution to the problem: in experiments some cut-offs are introduced spontaneously. For instance, electrons of sufficiently high energy, so called delta electrons, can be identified as separate tracks by the detector. This provides a cut-off in the energy distribution of primary electrons. A second cut-off comes from a probability argument. For any data set, there is always a largest observed cluster size from highest observed energy transfer, which in practice can also be considered as a cut-off.
3.2 Amplification on the sense wires

The ionization electron signal is amplified through avalanche mechanisms at the sense wires. The electric field inside a grounded tube of radius $R$, with a wire of radius $r_0$ at potential $V_0$ in the middle is given by

$$E_{\text{free}} = \frac{V_0}{r \ln(R/r_0)}$$  \hspace{1cm} (3.5)

where $r$ is the distance to the wire centre. As an electron approaches the wire, it feels the field increasing. Once the field is large enough, so that the electron can pick up a sufficient amount of energy to induce ionization between collisions with the gas molecules, a second electron is knocked out from an atom and a multiplication process starts (fig. 3.5). This amplification is exponential, with the number of electrons growing in successive generations on the approaching side of the wire. When all electrons have been collected on the wire, the avalanche is over. As long as the avalanche-induced changes on the electric field around the wire remain negligible compared to the wire field, the final number of ionization ions, and hence the signal, is proportional to the initial number of electrons. The proportionality constant $G$ is called the gain. Throughout this chapter it is assumed that the geometry, potentials and choice of gas within the time projection chamber are tuned to give a proportional response, i.e. a gain $G$ independent of the initial charge.
3.2.1 Townsend coefficient

The multiplication of ionization in the avalanche is expressed using the Townsend coefficient $\alpha$ as

$$dn_e = n_e\alpha ds$$

where $n_e$ is the number of electrons and $ds$ is the depth increase of the avalanche. Contemplating energy transfer processes, one realises that the Townsend coefficient depend on the gas in a complicated manner. Generally it can be obtained either from simulation or measurements, but not from analytic expressions. For a given chamber, the process can be approximated to be dependent only on the electric field. The avalanche would then start at a minimum field value $E_{min}$, and continue with increasing strength toward the sense wire at the radius $r_0$. By integrating the amplification over the avalanche an expression for the gain can be obtained

$$G = \frac{n_e(\text{final})}{n_e(\text{initial})} = \exp \left[ - \int_{r(E_{min})}^{r_0} \alpha(E) dr \right] = \exp \left[ \int_{E_{min}}^{E(r_0)} \frac{\alpha(E)}{\Delta E/ds} dE \right]$$

(3.7)

The two limiting cases of multiplication processes in low electric field far from the wires and high electric field close to the wires are treated in the following.

Ionization far from the wire

Far from the wire the electric field is still relatively weak and the mean free path, $\lambda$, is much smaller than the distance $ds$ required for the electron to pick up enough energy for ionization. With the mean ionization energy $\Delta V$, this assumption can be expressed as

$$\lambda \ll ds = \Delta V/E$$

(3.8)

Neglecting $\lambda$ as compared to $ds$, the electron can be assumed to immediately ionize a gas molecule as soon as it has enough energy. Extrapolating the approximation to the sense wire, the gain is determined by the potential difference between the field threshold $E_{min}$ and the wire radius $r_0$, divided by the average ionization energy $\Delta V$. Expressing those assumptions in the Townsend coefficient gives

$$\alpha = \frac{\ln 2}{E \Delta V}$$

(3.9)

An expression for the gain $G$ is obtained by inserting the electric field of equation (3.5). It is called the Diethorn formula

$$G = \frac{V_0}{E_{min} r_0 \ln (R/r_0)} \exp \left[ \frac{V_0 \ln 2}{\Delta V \ln (R/r_0)} \right]$$

(3.10)
The parameters of the Diethorn formula is found from a fit to data. For the HARP gas mixture (90% Ar + 10% Methane) the mean ionization energy is \( \Delta V = 23.6 \, \text{V} \), and the threshold electric field is \( E_{\text{min}} = 48 \, \text{kV/cm} \).

**Ionization close to the wire**

Very close to the wire, the field strengths are very large. Here the distance to pick up enough energy for ionization is much smaller than the mean free path \( \lambda \)

\[
 ds = \Delta V / E \ll \lambda \quad (3.11)
\]

Extrapolating this approximation from the wire to the radius where the field reaches threshold \( r(E_{\text{min}}) \), the gain will now be determined by the distance from \( r(E_{\text{min}}) \) to the wire at \( r_0 \). For the wire inside a tube (equation (3.5)) the gain will have the form

\[
 G = \exp \left[ \frac{\ln 2}{\lambda} \left( \frac{V_0}{E_{\text{min}} \ln(R/r_0)} - r_0 \right) \right] \quad (3.12)
\]

**3.2.2 Gain distributions**

The random nature of the multiplication process gives a gain which varies according to a given distribution. In the region of proportionality, the total gain distribution for an electron population can be computed on the basis of the gain distribution of an individual electron. If the initial number of electrons is large enough, the central-limit theorem states that the gain distribution for the entire electron population should become Gaussian. Some models for the one electron gain distribution will be presented below.

**Yule-Furry approximation**

Yule-Furry assumed that the probability for the creation of an electron \( p_{\text{birth}} \) in an avalanche was proportional to the number of electrons present \( n_e \) at a given moment, with a probability expressed as

\[
 p_{\text{birth}} = n_e \lambda \Delta \tau \quad (3.13)
\]

where \( \tau \) is a time like parameter, \( \Delta \tau \) a time step in this parameter and \( \lambda \) a proportionality constant. In the limit of high \( n_{\text{mean}} \) the probability distribution for the number of electrons obtained from one original electron becomes an exponential.

\[
 P(n) = \frac{1}{n_{\text{mean}}} e^{-n/n_{\text{mean}}} \quad (3.14)
\]

with the variance \( \sigma^2 = n_{\text{mean}}^2 \).
Figure 3.6: A good approximation of the distribution of the gain of an avalanche is the Polya distribution. It is characterised by a damping factor $b$. In the figure the Polya distributions for $b=0.1, 0.2, 0.4, 0.6, 0.8$ and $1.0$ are shown. For the limiting case $b=1$ the Polya becomes an exponential distribution, and for $b=0$ it becomes a Poisson distribution. Note that the y-axis has a logarithmic scale.

**Poisson approximation**

If instead the probability of the creation of an electron is assumed independent of the number of electrons present,

$$p_{\text{birth}} = \lambda \Delta \tau$$

the gain will follow a Poisson distribution.

**Byrne approximation**

In the Byrne approximation the probability of the birth of an electron is expressed as a combination between the two processes mentioned above, with one part proportional to the number of electrons and one part constant

$$p_{\text{birth}} = n\lambda \theta(r) \left( b + \frac{1-b}{n} \right) \Delta \tau$$

(3.16)

Here $\lambda$ is the mean free path and $\theta(r)$ is a radius dependent function, including such effects as the electric field dependence on radius. The parameter $b$ of the Byrne process allows for a tuning of the dampening of the amplification with the development of the avalanche and is determined by fits to data. The analytic expression obtained is the negative binomial distribution which at the limit of large $n_{\text{mean}}$ can be simplified using Stirling’s formula to the Polya distribution shown in figure 3.6

$$P(n) = \frac{1}{bn_{\text{mean}}} \frac{1}{k!} \left( \frac{n}{bn_{\text{mean}}} \right)^k e^{-n/bn_{\text{mean}}}$$

(3.17)
where \( k = 1/b - 1 \). This distribution has the width \( \sigma^2 = b n_{\text{mean}}^2 \). When \( b \) is large (small dampening) the distribution approaches an exponential as in the Yule-Furry case. For small values of \( b \) (large dampening) the distribution is more Poisson like. The Polya distribution has been used to successfully fit multi particle distributions.

### 3.3 Creation of the signal on the pad plane

After the avalanche is over, the electrons are quickly collected on the sense wire, leaving a cloud of slower ions behind. The ions produced in the avalanche induce a negative charge on the pad plane surface. The induced charge on the pad plane can be found from the method of reflecting charges, assuming a linear ion charge density \( \lambda \) along the sense wire at a distance \( D \) from the pad plane and the same distance \( D \) from the cathode wire plane. It has a distribution whose surface density \( \sigma \) is

\[
\sigma(x) = \frac{-\lambda}{2D \cosh(\pi x/D)}
\]

where \( x \) is the transverse distance to the sense wire. The pad response function, giving the total amount of induced charge on one pad as a function of the transverse distance between the pad centre and the charge, is obtained through integration over the surface charge on the pad. For the HARP TPC the pad response function is well approximated by a Gatti-Mathieson function presented in chapter 4 (fig. 4.14).
Chapter 4

Experimental setup

The HARP spectrometer in the CERN East Hall was taking data on proton collisions with solid targets during 2001. In 2002 complementary targets, including cryogenic liquid targets, will complete the data collection. In this chapter an overview of the HARP setup (figure 4.1) is presented, with the emphasis on functionality.

4.1 Beam

HARP uses a momentum selected secondary beam produced in a fixed target with protons from the PS\(^1\). The outgoing beam is composed of pions, protons, electrons, muons, kaons, deuterium and even triton. The composition depends on the momentum of the beam, a typical case for 3 GeV is shown in figure 4.2. One sees that the beam is dominated by protons and pions with small fractions of kaons, deuterons and tritons. The beam tuning is handled by magnets and collimators upstream from the target and the momentum selection is handled by a dipole magnet and a collimator and focusing by quadrupole magnets.

For the beam particle identification there are two systems: the time-of-flight (TOF) system and the threshold Cherenkov counters. The TOF system consists of two scintillator planes (TOF-A and TOF-B in fig. 4.3) 21 m apart with a time resolution of 170 ps. With the nominal momentum \( p \) of the beam particles known, the particle mass (identity) can be determined from the time difference \( \Delta t \) between the signals in the two planes and the distance \( s \) between the planes according to the formula

\[
m = \sqrt{\left(\frac{\Delta t p c^2}{s}\right)^2 - p^2}
\]

The TOF scintillator also has the role of defining the reference time of the event.

\(^1\)The proton synchrotron at CERN
**Figure 4.1:** The HARP detector setup in the PS-beam line. The target is situated inside the central tracker, the TPC detector. The TPC detector is surrounded by a resistive plate chamber (RPC) barrel and a solenoid magnet. Following the beam downstream from the target one encounters a forward trigger plane (FTP), a forward resistive plate chamber (RPC), a first drift chamber module (NDC) with four chambers, a dipole spectrometer magnet, a second drift chambers module (NDC), a Cherenkov counter, a third set of drift chambers (three modules with four chambers each), a time-of-flight (TOF) wall and a muon and electron identifier.

**Figure 4.2:** The time-of-flight (TOF) spectrum at a beam particle momentum of 3 GeV/c. The beam particles are nicely isolated into Gaussian peaks and one sees that the fraction of kaons, deuterons and tritons in the beam is much smaller than the fraction of pions and protons. The electron background has been rejected by using the beam Cherenkov counters.
<table>
<thead>
<tr>
<th>Beam Energy [GeV]</th>
<th>Electron tagging</th>
<th>Pion tagging</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 5</td>
<td>BCB at 1 bar</td>
<td>TOF</td>
</tr>
<tr>
<td>5</td>
<td>BCA at 0.6 bar</td>
<td>TOF and BCB at 2.5 bar</td>
</tr>
<tr>
<td>&gt; 5</td>
<td>Electron identifier</td>
<td>BCA at 1.25 bar and BCB at 1.5 bar</td>
</tr>
</tbody>
</table>

Table 4.1: Strategy for electron and pion tagging in the beam

Two threshold Cherenkov counters (BCA and BCB in fig. 4.3) filled with CO₂ gas provide particle identification through detection of Cherenkov light. Cherenkov light is emitted when the velocity of a particle exceeds the velocity of light in the medium in which it travels, i.e. when \( \beta = \frac{v}{c} > \frac{1}{n} \). The refractive index \( n \) of the medium can be tuned by changing the gas pressure and the gas. This makes it possible to obtain efficient tagging at several beam momenta using the same beam Cherenkov detectors at different pressures. The full scheme of pion and electron tagging is listed in Table 4.1.

The beam particle trajectories are tracked by four Multi-Wire Proportional Chambers (MWPC) shown in figure 4.4. Each chamber in the MWPC consists of one centred cathode plane with two planes of anode wires on the sides, rotated at 90 degrees to each other. The two planes with different orientations allow to reconstruct a three dimensional position in each chamber along the trajectory. By combining measurements from the four chambers the direction of the beam particles is obtained. [19]

4.2 Trigger

Under normal running conditions there are two kinds of triggers: a beam trigger for when a desired beam particle is moving towards the target and an interaction trigger for when a candidate for a secondary particle is detected. The trigger system is strongly interconnected with the beam monitoring system, sharing subsystems such as beam Cherenkovs, used to veto the electron contamination of the beam. Further components of the beam trigger system are two beam halo scintillators (Halo-A and Halo-B), with different acceptance, which veto the non collimated component of the beam. Closer to the target is a target defining scintillator disc (TDS) detecting particles moving towards the target position.

Secondary particles produced at large production angles are detected by an inner trigger chamber (ITC) with scintillating fibres arranged in a cylinder surrounding the target. The ITC has three layers of scintillator tubes, giving an overall efficiency above 99% [18]. Secondary particles at small production angles are detected by a forward scintillating trigger plane (FTP) just after the central TPC tracker. The FTP consists of two perpendicular planes with seven scintillator units each. In the centre of the FTP is a 6 cm
Figure 4.3: The beam monitoring and triggering system of HARP. The beam is marked with a dotted line coming in from the left in the picture. The target is located inside the ITC. The sub triggers are described in the text (apart from the BS3 which is no longer in use).

Figure 4.4: In HARP there are four MWPC chambers used for beam tracking. Each chamber has one central cathode plane and two planes with anode wires rotated at 90 degrees to each other.
<table>
<thead>
<tr>
<th>Material</th>
<th>Z</th>
<th>0.02(\lambda) (cm)</th>
<th>1.0(\lambda) (cm)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>4</td>
<td>0.81</td>
<td></td>
<td>0.5(\lambda) (MiniBooNE)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MiniBooNE target replica</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>0.76</td>
<td>38.01</td>
<td>0.5(\lambda) (K2K)</td>
</tr>
<tr>
<td>Al</td>
<td>13</td>
<td>0.79</td>
<td>39.44</td>
<td>K2K target replica</td>
</tr>
<tr>
<td>Cu</td>
<td>29</td>
<td>0.30</td>
<td>15.00</td>
<td>button target</td>
</tr>
<tr>
<td>Cu</td>
<td>29</td>
<td></td>
<td></td>
<td>skew target</td>
</tr>
<tr>
<td>Sn</td>
<td>50</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ta</td>
<td>73</td>
<td>0.22</td>
<td>11.14</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>82</td>
<td>0.34</td>
<td>17.05</td>
<td></td>
</tr>
<tr>
<td>(H_2)</td>
<td>1</td>
<td></td>
<td>6 cm</td>
<td></td>
</tr>
<tr>
<td>(D_2)</td>
<td>1</td>
<td></td>
<td>6 cm</td>
<td></td>
</tr>
<tr>
<td>(N_2)</td>
<td>7</td>
<td></td>
<td>6 cm</td>
<td></td>
</tr>
<tr>
<td>(O_2)</td>
<td>8</td>
<td></td>
<td>6 cm</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: HARP targets

hole for the beam to pass through.

The triggering logic has been optimised for different conditions: considering the thickness of the target, the energy of the beam, and incoming beam particles. For thick targets, about 63% of the beam particles have hadronic interactions and it is sufficient to require only a beam trigger to get a sample of data with a high fraction of hadronic interactions. For thin targets only \(\sim 2\%\) of the beam particles have hadronic interactions and to obtain a pure sample of hadronic interaction data, a forward or a central interaction trigger is required as well. At low beam momenta (below 4 GeV/c) elastic proton scattering dominates the reactions in the forward direction. To enrich the data with inelastic pion production reactions, a forward trigger discriminating low energy scattered protons from pions is required. The forward threshold Cherenkov detector, which will be described in detail later, can be used for this purpose [13]. Other trigger conditions can be set for calibration runs, for example to select cosmic rays in the TPC. This case will be described in detail in chapter 6 and 7. To ensure absolute normalisation, a down scaled set of data with randomly chosen beam triggers is also stored.

### 4.3 Target

The target is located inside the central tracker (TPC) 50 cm downstream of the read-out chamber inside a cylindric cavity of 5 cm radius, a construction
Figure 4.5: A cut of the HARP central tracker: the time projection chamber (TPC). The beam comes in from the right in the picture impinging on the target half a meter from the pad plane. The target is situated inside a cylinder surrounded by an inner field cage and an inner trigger chamber in the middle of the TPC. Around the TPC are two layers of resistive plates (the RPC-barrel) and a solenoid magnet that extends about half a meter after the TPC drift volume.

which allows for a fast change of targets. The TPC and the cylinder (inner field cage) is shown in fig. 4.5. The bulk of targets are thin solid discs with a diameter of 30 mm and a thickness between 2.2 mm and 8.1 mm. They are chosen to be 2% of an hadronic interaction length $\lambda$ to minimise re-interactions while keeping a reasonable hadronic interaction rate. A number of thick targets are also used with the primary aim of checking the simulation of re-interactions. For the measurements on cryogenic targets a standard container with a length of 6 cm is used. The targets are tabulated in table 4.2.[22]

4.4 Resistive Plate Chambers

The central tracker of the HARP experiment is the time projection chamber (TPC) to be described in detail later in this chapter. The TPC is surrounded by a resistive plate chamber (RPC) detector barrel which is squeezed in, into 24 mm of space, between the TPC and the solenoid coil [17]. The RPC is used for particle identification from time-of-flight measurements. The TPC, the RPC, the solenoid coil and the return yoke are shown in figure 4.5. The RPC barrel has two partly overlapping layers of 15 resistive plate chambers
Figure 4.6: In each resistive plate chamber are four gas gaps where fast avalanches are created at the passage of charged particles. The glass layers in between serve as capacitors to protect the conductive parts. The avalanches induce a signal in the central plane where the readout is made.

Each chamber is segmented in the longitudinal direction into seven pads. Downstream of the TPC is a forward RPC detector plane serving the same purpose as the barrel RPC. The forward RPC detector consists of eight chambers in the horizontal and eight chambers in the vertical direction. This renders a total of 322 RPC pads, covering a large region of production angles. The design of an RPC chamber is shown in fig. 4.6. Each resistive plate chamber has four gas gaps with very high electric fields where fast avalanches are created at the passage of charged particles. The current is hindered from flowing freely by insulating glass layers between the metal and the gas. The avalanche induces a signal in the central plane which is read out and digitised by time-to-digital converters (TDC). To separate particles based on the time-of-flight difference on the short distance (40 cm) from the target to the outer barrel, the RPC pads need a very good time resolution. The HARP RPC time resolution is of the order of 150 ps.

4.5 NOMAD drift chambers

Particle tracking in the forward direction is performed by 23 drift chambers obtained from the NOMAD experiment. Apart from three chambers inside the electron identifiers, the chambers are grouped into five modules with four chambers each. The positions of the modules are shown in grey in figure 4.7, note that the three last units are part of the muon identifier and will not be described here. The first module is situated directly after the TPC. It consists of four drift chambers with three gas layers each with sense wires inside. The sense wires in the first gas layer are rotated by -5 degrees with respect to the second, and the sense wires in the last layer are rotated by the same angle in the other direction. This pattern is repeated for each of the 23 chambers. A charged particle traversing the detector ionises the gas (90% argon-9% CO₂-1%CH₄) giving electrons that create avalanches
Figure 4.7: The layout of the HARP detector. The grey blocks are modules with four NOMAD drift chambers each. The last three blocks are single chamber modules inside the electron and muon identifier.

on sense wires within the gap.\(^2\) The signal is read directly from the sense wires [21]. In the first set of drift chambers the transverse position of the particle is reconstructed and the direction of its momentum is found under the assumption that the particle originates at the target, 2 m upstream. After the first module of drift chambers, a dipole spectrometer magnet with a vertical field of 0.68 Tm bending power deflects the trajectory of charged particles (\(ze\) is the particle charge) according to

\[
\theta = \frac{0.3z d|m|B[T]}{p_T[GeV/c]}
\]

where \(\theta\) is the deflection angle in the horizontal plane, \(p_T\) is the momentum in the horizontal plane, \(B\) is the magnetic field and \(d\) is the distance travelled within it. The magnet gives a 40 mrad direction change for 5 GeV/c particles. A second module (four chambers) is situated just after the spectrometer. By using information from this module together with the remaining three modules (four chambers each) further down the beam line, it is possible to reconstruct track segments of the particle trajectory behind the magnet. The deflection angle gives the momentum and the charge of the particle [14].

4.6 Cherenkov detector

The Cherenkov detector, filled with a high density gas \((C_4F_{10})\) at atmospheric pressure, is used to separate hadrons in the forward direction. As

\(^2\)A description of the principle of ionization by charged particles traversing a gas and amplification avalanches can be found in chapter 3.
4.8 Electron and muon identifiers

Particles are sometimes accompanied by knock-on electrons in the Cherenkov counter and are easily marked as electrons. To reveal these electrons, a 10 radiation lengths deep electromagnetic calorimeter is used. Behind the electromagnetic calorimeter, a small hadronic calorimeter, 6.4 layers deep, filters out the bulk of the forward hadrons hitting the photon layer and the calorimeter allows to reconstruct the position of the photon. The electromagnetic calorimeter based on the scintillator plates, detecting muons with path through the electromagnetic calorimeter are a scintillator plane, detecting muons which pass through the electromagnetic calorimeter. [26].

The particle velocity is measured by the time-of-flight from the target to the time-of-flight (TOF) wall. The scintillator light in the three layered TOF wall is led through fiber-optic light guides into photo multipliers at both ends of the wall and read out. [17]

Table 4.3: Threshold values for the forward Cherenkov detector.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons</td>
<td>26 GeV/c</td>
</tr>
<tr>
<td>muons</td>
<td>17.6 GeV/c</td>
</tr>
</tbody>
</table>

The light produced in the gas is guided by mirrors towards Winston cones and into 28 photo multipliers where the signal is amplified and read out.

In section 4.1, a particle with a velocity above threshold $\beta > 1$ produces Cherenkov light on its way through the detector. Threshold energies in the HARP forward Cherenkov are listed in Table 4.3. The number of photomultiplier tubes and their threshold energies depend on the velocity of the particle. Using the Cherenkov radius, the particle's velocity is above threshold if the Cherenkov radius is smaller than the threshold radius.
and hadronic calorimeters. The muon identifier is used not only to detect muons from secondary pion decays, but also to monitor the muon contents of the beam.

### 4.9 Time Projection Chamber

The central tracker used in HARP is the time projection chamber (TPC). It has two parts: a 1.5 m long cylindrical gas filled drift space and a chamber at the upstream end of the drift space. Charged particles passing through the drift space create ionization electrons along their path. The active volume is surrounded by a field cage providing a voltage gradient of 120 V/cm along the cylinder axis. The electric field pulls the ionization electrons towards the chamber where the signal is amplified and recorded. The TPC is immersed in an axial magnetic field of 0.7 T bending the particle trajectory according to

\[ p_T[GeV/c] = 0.3zB[T]R[m] \]

where \( z \) is the charge of the particle, \( B \) is the magnetic field, \( R \) is the radius of curvature and \( p_T \) is the particle transverse momentum with respect to the beam direction. This field is provided by a magnet with a copper solenoid coil and an iron return yoke. The construction of the HARP TPC will be described below whereas the principles of drift chambers were explained in more detail in chapter 3. The layout of the TPC and the solenoid magnet is shown in figure 4.5 and some geometrical data are listed in table 4.4.

#### 4.9.1 Field cage

The electric field in the drift volume of the TPC is determined by a high voltage plane on the downstream end of the barrel, a grounded cathode wire plane in the chamber and an outer and an inner field cage (fig. 4.8). Both of the field cages consist of conductive strips at precise potentials, attached to insulating Stesalit cylinders onto which support bars (24 for the outer field
Figure 4.8: The electric field in the drift volume is determined by a high voltage plane (to the right in the picture) and a grounded cathode wire plane (to the left in the picture), an outer and an inner field cage with conductive strips put at precise potentials.

Figure 4.9: The outer field cage has three layers of conductive strips. The layer closest to the drift space (the upper layer in the figure) provides the potential gradient. The one below makes the electric field more homogeneous. The third layer positioned within the dielectric is there to avoid field ejection due to the potential difference between the grounded outside of the barrel and the potentials of the strips.
cage and 12 for the inner field cage) are glued. Facing the drift space there is a layer of 10 mm metallized Mylar strips, separated by 1 mm gaps, precisely positioned on the support bars. Below the mylar strip layer on the surface of the Stesalit cylinders, there are 10 mm wide potential rings of printed copper on a Kapton foil separated by 1 mm gaps inside the gas volume. For the outer field cage a third layer of conducting strips inside the Stesalit is shielding the chamber gas from field ejection, caused by the potential difference between the grounded surface on the outside of the barrel and the higher potential strips (fig. 4.9). This gives three layers of strips, at a pitch of 11 mm shifted by half a period to each other. Between adjacent strips there is a potential difference, which determines the axial electric field in the drift volume. The field is mainly determined by the layer facing the drift volume, as will be shown in chapter 5. The middle strip layer has the role of minimising field distortions close to the barrel. The strips in this layer are shifted by half a period to the layer above, changing both their longitudinal position and their potential. For the inner field cage, the solution adopted to shield the drift space from field ejection is slightly different because of the limited space and the limited amount of insulator. Here the third layer is missing, instead five different strips at increasing potential have been etched on the inner surface of the inner field cage. Simulation of the design of the strip structure and the consequences of field inhomogeneities in the drift space will be treated in chapter 5.

4.9.2 TPC gas choice

For the HARP TPC active volume a known and well documented gas has been chosen: a mixture of methane (10%) and argon (90%) held at atmospheric pressure. Apart from basic measurements on gas characteristics existing in literature, extensive simulations have been performed before construction, to determine how the gas mixture behaves for the HARP TPC conditions, with axial electric and magnetic fields, $E = 120$ V/cm and $B = 0.7$ T [24]. The axial magnetic field of 0.7 T, meant to make momentum measurements possible, has the additional advantage of limiting the diffusion of drifting electrons. At $B = 0.7$ T the HARP gas has a transverse diffusion of approximately 200 $\mu$m for 1 cm of drift. This gives a dispersion of 2.5 mm over the maximum drift distance (1.5 m). Longitudinal diffusion, on the other hand, is about 380 $\mu$m per cm of drift, translating to a dispersion of about 85 ns for signals from the far end of the active space, and is not affected by the B-field. In the HARP gas mixture, it is mainly argon atoms that are ionised with a most probable ionization rate of about 50 electrons per cm [24]. The methane molecules serve as quenchers reducing the sparking risk and also increasing the drift velocity.
<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol Definition</th>
<th>Argon</th>
<th>Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$\rho [g/cm^2]$</td>
<td>$1.66 \times 10^{-3}$</td>
<td>$6.74 \times 10^{-4}$</td>
</tr>
<tr>
<td>Energy loss density</td>
<td>$dE/dx [keV/cm]$</td>
<td>2.44</td>
<td>1.48</td>
</tr>
<tr>
<td>Effective ionization energy</td>
<td>$W [eV]$</td>
<td>26</td>
<td>28</td>
</tr>
<tr>
<td>Primary electrons</td>
<td>$e^- [cm^{-1}]$</td>
<td>29.4</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 4.5: Gas data. Ionization yield are given for minimum ionizing particles [26].

Figure 4.10: The TPC pad plane has a hexagonal geometry with six sectors separated by spokes that hold sense wires, cathode wires and gate wires. The wires are strung as a spider web on the spokes and the outer wheel.

Figure 4.11: A schematic drawing of the TPC chamber, showing the three different wire planes and the pad plane below.
4.9.3 TPC Chamber

The TPC chamber marks the end of the TPC drift space at the upstream end of the barrel. In the chamber, the ionization electrons are multiplied by electromagnetic avalanches on the sense wires and a signal is induced in the pads, connected to electronics for shaping and further amplification of signals. The basic geometry of the chamber is that of a small inner wheel connected to a large outer wheel by six spokes, as can be seen in figure 4.10. The spokes hold up the hexagonal wire structure of the chamber and serve also as voltage providers to the wire planes.

Spoke structure

The 7 mm thick spokes of the wheel extend 21 mm from the pad plane towards the drift space, ending with a thin copper guard ring. The guard ring prevents the spokes from polarising and distorting the field nearby. A detailed simulation of this effect is treated in chapter 5. The spokes hold a gate wire grid, which is protecting the active volume from charge-up, cathode wires setting the ground surface of the drift volume, and sense wires, where the signal is amplified. The wire structure has an hexagonal “spiders web” shape co-axial to the beam direction (figure 4.10 and 4.11). Information about the different wire planes can be found in table 4.6 and the sense wires and gate wires are further described below.

Gate wires

As an ionization electron drifts towards the chamber, it passes gate wires strung on the spokes, 16 mm from the pad plane. During readout the gate wires are all put at the nominal voltage of their position in the drift field. Outside the readout period every wires put at a potential higher than nominal are alternated with wires put at a potential lower than nominal (±35 V). This scheme creates an electrostatic barrier for ions from the avalanche and as such prevents them from drifting into the detector creating charge-up on dielectric surfaces and within the gas. It also stops part of the drift electrons within the drift space to reach the sense wires and create avalanches outside the readout period.\(^3\) The drift paths of electrons moving from the drift space toward the chamber are shown in figure 4.13. The upper picture shows the drift paths of electrons with a closed gating grid and the lower picture shows the drift paths of electrons with an open gating grid [2]. The gate wires, put at different potentials, have to be electrically isolated from each other and are therefore displaced about 100 \(\mu m\) from each other in the \(z\)-direction. Simulation have shown that this should neither intervene with

---

\(^3\)In fact the electrons will in this configuration mainly follow the B-field lines because of the \(\omega r\)-effect[7], while ions follow the E-field lines. Therefore a closed grid is partially transparent to electrons, being fully opaque to ions.
Figure 4.12: Each TPC sector is covered by pads 662 in 20 rows, each at a fixed radius. Each pad has a length of 15.5 mm in the radial direction and width of about 6.5 mm in the theta direction.

Figure 4.13: The functionality of the wiring scheme showing the drift lines for electrons with the gating grid closed (upper picture) and open (lower picture). The horizontal axis in the picture represents the cylinder axis, the vertical the radial axis and the wires extend in the theta direction pointing inwards in the picture. In the HARP TPC the radial length of a pad is 15.5 mm, which is approximately the width of the drift cell shown in the picture.

<table>
<thead>
<tr>
<th>Wire type</th>
<th>Thickness</th>
<th>Pitch</th>
<th>Distance to pad plane</th>
<th>Potential</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sense wires</td>
<td>20μm</td>
<td>4 mm</td>
<td>5 mm</td>
<td>1500 V</td>
<td>W/Au</td>
</tr>
<tr>
<td>Cathode wires</td>
<td>80μm</td>
<td>2 mm</td>
<td>10 mm</td>
<td>0 V</td>
<td>Cu/Be</td>
</tr>
<tr>
<td>Gate wires</td>
<td>80μm</td>
<td>2 mm</td>
<td>16 mm</td>
<td>Nominal</td>
<td>Cu/Be</td>
</tr>
</tbody>
</table>

Table 4.6: Wire data
Figure 4.14: The pad response function describing the signal charge induced in a pad from an avalanche at a distance from the pad centre. The dots are the measured values for the HARP TPC prototype, the TPCino. The pad width is 6.5 mm and the $\sigma$ of the pad response function is 3.6 mm.

the functionality of the gating grid nor disturb the coordinate measurement of the detector [24].

Sense wires

After passing the ground plane of the drift space (the cathode wires 10 mm from the pad plane) the electron starts to feel the increasing electric field from the sense wire grid 5 mm away. It is accelerated and knocks out electrons from atoms of the chamber gas and an amplification avalanche has started (see chapter 3 for details). The TPC has a novel design, where a single sense wire is strung in a spiral from start to end. This is possible since the sense wire signal is not read out, with the important advantage of higher reliability and smaller dead zones. Within each spoke there is a conductor at 1.5 kV, serving the double purpose of providing the voltage to the sense wires and decreasing the risk of field ejection close to the dielectric spokes. Simulation providing input to this design is reported in chapter 5. There the stringing pattern is also shown in more detail (fig. 5.19).

Readout pads

The spokes of the wheel divide the chamber readout plane into six sectors, each covered by 662 readout pads divided into 20 rows. Each pad has a 15.5 mm length in the radial direction and a width of approximately 6.5 mm. The pads of one sector are shown in fig. 4.12. When the ionization avalanche is over, the electrons quickly reach the sense wire and disappear leaving the slower ions behind. The positive ion cloud induces a negative signal on
the conductive readout plane. The charge induced in one readout pad as a function of the transverse distance between the avalanche and the pad centre is called the pad response function, for HARP this pad response function has been found to be well approximated by the Gatti-Mathieson function, with the fitted parameter $K_3 = 0.5$ [24]. The measured pad response function for a small TPC prototype, called the TPCino, is shown in figure 4.14. The induced charge in the pad plane and the pad response function is treated in more detail in chapter 3.

**Analogue electronics**

The pad plane is physically an electronic printed circuit board which contains the electronics amplifying the induced signals in the pad plane. It is built up by six identical 6-layer mother boards, one for each sector of the TPC. The signal from a readout pad is fed into a pre-amplifier circuit, one pad mapped onto one pre-amplifier. The pre-amplifiers are mounted in sets of four inside each chip, sharing common voltage supplies. The pre-amplifier shapes the signal before it is led through a micro-flex cable to an external daughter card. Each flex has a capacity of 24 pad channels plus low voltage supplies and ground for the amplifier circuits. A small number of the chips (<5%) have two different voltage supplies from two different flexes. Minor instabilities in these voltage regulators result in a slightly varying voltage over the amplifier circuit within the chips. This has been found to be the cause of an unstable baseline for a set of noisy pads which will be treated further in chapter 6. The daughter card is in turn connected through coaxial cables to analogue to digital converters (ADCs).[27]

**Digital electronics**

The ADCs sample the analogue signals with a clock frequency of 10 MHz. Since the TPC drift time is approximately 30 $\mu$s, the readout of about 1000 events per 400 ms spill, gives 300 000 time samples per pad per spill. Without any suppression of signals below threshold and with a sample size of a 10-bit word, a raw data volume of 1.5 GByte is obtained for each spill, which could be clearly difficult to handle. Zero suppression can in ideal cases reduce this data volume by two orders of magnitude (neglecting for example noisy pads). The baseline threshold of the ADC is called the pedestal. It is set at the average amplitude of noise for each pad, computed from the raw noise signals during three empty events. The pedestal is computed at the start of each run, stored internally within each ADC and automatically subtracted from signals arriving to the ADC. After pedestal subtraction there is an additional threshold of 10 ADC counts, to trigger the data recording. Since the ADC also allows for pre- and post-sampling, the signal seen by the data acquisition consists of three samples before the signal reaches thresh-
old, the signal above threshold, and three more samples after the signal has
gone below threshold again. Negative signals (below pedestals) are set to
zero and suppressed.

4.10 Signal shape in the TPC

The transfer function of a circuit is the electronics response to a charge delta
pulse on the readout pad. The analogue electronic chain, from pre-amplifier
to before digitisation, would give a transfer function well approximated by
a gamma function as seen in figure 4.15.[28] The gamma function is charac-
terised by the parameter $\tau$ as,

$$I(t) = \frac{t^2}{\tau^2} \exp \left(-\frac{t}{\tau}\right)$$

The parameter $\tau$ would be about 70 ns for a delta pulse, giving a full
width half maximum (FWHM) of about 240 ns. However, the signal induced
by a single electron is not a delta function, but rather an exponential. The
long tail of the exponential increases the parameter $\tau$ of the readout signal
to 95 ns and the FWHM to 320 ns. The electrons that induce the signal on
a given pad have followed slightly different paths around the wires inside the
readout cell, giving a spread in the drift times called collection isochrony.
In HARP, the collection isochrony is of the order of 100 ns. Another effect
comes from particle trajectories inclined with respect to the pad plane. As
the distance between the track and the pad plane varies, it results in a a
difference in drift time for electrons from different parts of the track, even
over a pad. This time spread is called drift isochrony and varies strongly
with the angle of the track. For tracks with a 20 degree angle against the
pad plane ($\theta = 70$ deg) the drift isochrony over a pad is about 100 ns. For
60 degrees ($\theta = 30$ deg) this has increased to 470 ns and at higher angles it
increases almost as $\sim \tan(\pi/2 - \theta)$. Only the longitudinal diffusion, would,
for a drift of 150 cm, give a time spread of 85 ns. [24] These conditions are
in agreement with the laser signal shapes reported in fig. 4.15 [28].

4.11 Calibration systems of the TPC

The calibration of the TPC relies on three systems: cosmic rays, photo
electrons from laser pulses on aluminized fibres and energy deposition from
krypton decay within the detector.

4.11.1 Cosmic ray calibration

The cosmic ray calibration relies on the bulk of knowledge of the cosmic
ray spectrum which serves as a reference to which the HARP cosmic ray
Figure 4.15: The pad signal shape from the laser pulse. The HARP electronics circuit transfer function is well approximated by a gamma function with a nominal width of 240ns. The recorded signal is broadened by the tail of the electron signal, collection and drift isochrony and diffusion effects to a FWHM of about 0.6μs.

Figure 4.16: A schematic picture of the TPC laser calibration system. The laser light from an excimer laser is guided through optical fibres past the HV membrane at the downstream end of the drift space of the TPC.

data is compared. This is used in order to tune the scales between readout pads. The cosmic ray calibration work will be described in further detail in chapter 7.

4.11.2 Laser calibration

The laser system is used to increase the understanding of field inhomogeneities within the drift space. It is also used to continuously measure the drift velocity, which is dependent on temperature and pressure. The downstream end of the TPC drift space is marked by a constant potential conductive membrane, through which 198, 100 μm thick, optical fibres with aluminized tips enter through 4 mm diameter holes. A schematic drawing of the laser system is shown in fig. 4.16. The fibres transmit the UV laser light to the tip leading to emission of photo electrons as well as emission of free photons with large opening angles. When the laser fires, the free photons will reach all the inner surfaces of the TPC at once. Most surfaces will be unaffected by this low intensity illumination, except for the gold coated pad plane. The high atomic number of gold (Z=79) raises the cross section for
the photo electric effect, $\sigma_p \propto Z^5\lambda^{7/2}$, to levels where photo electrons are emitted all over the pad planes. The electrons start avalanches around the sense wires giving a first laser signal. The wave length of the KrF excimer laser is $\lambda=249$ nm which is below the aluminium threshold for the photo electric effect ($\lambda=296$ nm), the thickness of the aluminum coating has been tuned to give a sufficient intensity of photo electrons. During data taking the laser is fired twice per spill and photoelectrons drift through the TPC all the way to the pad plane where they induce a second laser signal. The transfer function for the TPC electronics is normally a gamma function, such as shown in figure 4.15. The time jitter between the laser and the start of digitisation of the signal gives the possibility to sample the signal much more finely than the nominal 100 ns, by using information from several events. Figure 4.15 shows the signal in one pad obtained through this technique. Since the exact position and the exact time of creation of the electrons is known, the time and position of the signal they induce in the pad plane can be used to understand field inhomogeneities, measure the drift velocity of the detector and examine pulse shapes.

### 4.11.3 Krypton calibration

The krypton calibration system aims to calibrate the digitized signals from the pad ADC to an absolute energy scale of ionization deposit. The same technique has been used successfully for drift chamber calibration before, for example in the ALEPH, DELPHI and NA49 experiments.

In a few calibration runs, the HARP TPC was filled with radioactive krypton gas $^{83m}$Kr, which was obtained from decay of the solid $^{83}$Rb. In this decay the ground state of krypton is not populated directly, but goes via intermediate levels. Figure 4.17 shows a schematic decay diagram for the process $^{83}$Rb$\rightarrow$+$^{83m}$Kr. The excited $^{83m}$Kr fills the TPC gas volume giving localised energy deposits evenly distributed over the pad plane. The decay chain can proceed via combinations of internal conversion electrons, Auger electrons and photons, giving a rich spectrum between 9 and 42 keV [26]. The energy spectrum obtained in the NA49 experiment is presented in figure 4.19. During krypton decay the isotropic illumination of the TPC pad plane is read out at random times (triggerless data taking) giving the readout of figure 4.18. The half-life of the main excited state $^{1/2}-^{83}$Kr is 1.83 hr. After about 3 half-lives have passed subsequent to krypton cut-off, the chamber can again be operated as normal.
Figure 4.17: The solid ground state of $^{83}$Rb (half life 86.2 days) decays to an excited state of the gaseous $^{83}$Kr (half life 1.83 h). During calibration runs, krypton gas was fed into the TPC gas system and decay signals were recorded.

Figure 4.18: A screen shot of the event display during triggerless krypton calibration runs. The energy deposit at krypton decay is localised to clusters in space, covering typically 5 pads.

Figure 4.19: The simulated response of $^{83m}$Kr in the NA49 TPC (left) and the measured response in the NA49 TPC (right). The resolution at the 41 keV peak is 5.3%. The gas used in the chamber was $ArCO_2CH_4$ (90:5:5) [26].
Chapter 5

Simulations of the Time Projection Chamber

The goal for the electrostatic design of the TPC is to obtain a homogeneous axial electric field in the whole drift space followed by a high and constant gain on the sense wires. Ideally, no ions should drift onto dielectric support structures and no electric distortions would give errors in the measurements. In order to design the TPC in a way that goes along these lines, simulations were performed before construction.\(^1\) This chapter describes the simulation procedure, after which calculations on drift distortions near the field cage, field ejections near the sense wire support, and drift distortions in the chamber will be discussed. The simulation uses a cartesian coordinate system adapted to the problem geometry case by case. The description provided is related to a common cylindrical coordinate system \(\{r, \theta, z\}\) defined in figure 5.4.

5.1 Simulation procedure

One way to simulate an electrostatic situation with a computer is to define a problem volume with boundary conditions, divide it into discrete elements and convert the continuous physical laws into a linear system of equations. In the electrostatic simulation presented, a commercially available program, Maxwell, has been used [31]. It solves the Laplace equation using the quadratic Finite Elements Method. The numerically obtained field map from Maxwell, can be used within the CERN developed program Garfield to perform Monte Carlo simulations of electron and ion drift. In this section the principles of the quadratic finite element method will be described and a few words will be mentioned about the Monte Carlo program Garfield before providing details of the simulation itself.

\(^1\)Performed by the author in the framework of the CERN summer student program.[30]
Figure 5.1: The basic element used in Maxwell is a ten point tetrahedron. This gives ten degrees of freedom for the values of the potential in the nodes. The variables \(L_1, L_2, L_3, L_4\) are equivalent to the triangular coordinates \((\zeta_1, \zeta_2, \zeta_3, \zeta_4)\).

5.1.1 The Quadratic Finite Elements Method

The basic principles of the quadratic finite element method implemented in Maxwell is described below. For further reference the reader is referred to WEB resources such as [29], [32] or [33].

Triangulation

First a problem volume with boundary conditions (symmetry or constant potential) is defined. Then the problem volume is split into small elements, which can be chosen in different ways. The mesh is built so that the entire problem volume is covered by mutually exclusive elements. In the program Maxwell, triangles are used in the two dimensional case and tetrahedrons in the three dimensional case. Concentrating on the three dimensional case, each tetrahedron is defined by ten points corresponding to vertices and midpoints of the sides (fig. 5.1). The vertices and the midpoints are shared between neighbouring elements.

Basis functions

Every vertex of a tetrahedron, as well as every midpoint of a side of a tetrahedron is associated with a quadratic basis function defined in the triangular coordinates presented in figure 5.2. The basis function associated to one point is normalized to unity at that point and to zero at all other points in the mesh, two conditions which totally determine the shape of the
Triangular Coordinates

\[ \zeta_1 = 0 \]
\[ \zeta_2 = 1 \]
\[ \zeta_3 = 1 \]

\[ \zeta_1 + \zeta_2 + \zeta_3 = 1 \]

**Figure 5.2:** Each side of the triangular element defines a zero line in the triangular coordinate system \([\zeta_1, \zeta_2, \zeta_3]\). At the opposite vertex the coordinate is unity and the midpoints of the two other sides have the value one half. In this way each combination of a side and vertex defines a coordinate. The three dimensional case is similar.

basis functions in the triangular coordinate system. We also note that this gives that each basis function covers only the nearest tetrahedrons. The basis functions on one tetrahedron \(i\) expressed in the triangular coordinates \((\zeta_1, \zeta_2, \zeta_3, \zeta_4)\) can represented in a ten dimensional column vector \(\phi_i\) as

\[
\phi_i(\zeta_1, \zeta_2, \zeta_3, \zeta_4) = \begin{pmatrix}
\zeta_1(2\zeta_1 - 1) \\
4\zeta_1\zeta_2 \\
\zeta_2(2\zeta_2 - 1) \\
4\zeta_1\zeta_3 \\
4\zeta_2\zeta_3 \\
\zeta_3(2\zeta_3 - 1) \\
4\zeta_1\zeta_4 \\
4\zeta_2\zeta_4 \\
4\zeta_3\zeta_4 \\
\zeta_4(2\zeta_4 - 1)
\end{pmatrix}
\]  
(5.1)

These basis functions are fixed in the triangular coordinate system but their shape in the \((x, y, z)\) space is determined by how the mesh is made.
Coefficients

Basically, the total potential will be built up by adding strictly localised quadratic peaks of different heights and shapes over the entire problem volume. The shape of the peaks are those of the basis functions, the coefficient (heights) of the peaks are given by the value of the potential at the points of the mesh. The potential on one tetrahedron is built up by the quadratic basis functions $\phi_n$, $(n = 1, 2, ..., 10)$ with coefficients determined by the node values of the ten points in fig. 5.1. The potential at the ten points,

$$u^T = (u_1, u_2, u_3, u_4, u_5, u_6, u_7, u_8, u_9, u_{10}) \quad (5.2)$$

multiplied by the vector $\phi_i$ gives the potential over the tetrahedron as

$$u(\zeta_1, \zeta_2, \zeta_3, \zeta_4) = u^T \phi(\zeta_1, \zeta_2, \zeta_3, \zeta_4) \quad (5.3)$$

In this way the mesh and the potentials at the nodes completely determine the numerical solution. The potential at the nodes $\{u_n\}$, will in turn be determined by Laplace’s equation and the boundary conditions as described below.

Building a linear system from the Laplace equation

The node values are found by minimizing the residuals of the Laplace equation. The residual is the difference between the true solution to the problem and the numerical approximation. In the so called Galerkin method, the residual is minimized by projecting the equation onto the space spanned by the basis functions. This means requiring that the scalar product between Laplace equation and each basis function is zero. The Laplace equation in the absence of charge is

$$\nabla^2 V = -\frac{\rho}{\varepsilon_0} = 0 \quad (5.4)$$

This equation is projected onto the set of basis functions, $\phi_m$, to which the potential at node $m$ is the coefficient

$$\int_\Omega \nabla^2 V \phi_m d\Omega = 0 \quad (5.5)$$

By using the Green-Gauss theorem:

$$\int_\Omega (f \nabla \cdot \nabla g + \nabla f \cdot \nabla g) d\Omega = \int_\Gamma f \frac{\partial g}{\partial n} d\Gamma \quad (5.6)$$

the scalar product can be rewritten as

$$\int_\Omega \nabla V \cdot \nabla \phi_m d\Omega = \int_\Gamma \frac{\partial V}{\partial n} \phi_m d\Gamma \quad (5.7)$$

58
The integrand on the left hand side is evaluated using \( V = \sum_n u_n \phi_n \)

\[
\nabla V \cdot \nabla \phi_m = \sum_n u_n \frac{\partial \phi_n}{\partial \zeta_i} \frac{\partial \phi_m}{\partial \zeta_j} \frac{\partial \phi_m}{\partial x_k} \frac{\partial \phi_m}{\partial x_k} \tag{5.8}
\]

Substituting the expression (5.8) into equation (5.7) a linear system of equations \( E_{mn} u_n = F_m \) is obtained, where \( E \) is called the stiffness matrix and \( F \) is called the load vector. The elements of \( E \) and \( F \) are

\[
E_{mn} = \int_\Omega \frac{\partial \phi_n}{\partial \zeta_i} \frac{\partial \phi_m}{\partial x_k} \frac{\partial \phi_m}{\partial \zeta_j} \frac{\partial \phi_m}{\partial x_k} \tag{5.9}
\]

\[
F_m = \int_{\Gamma} \frac{\partial V}{\partial n} \phi_m d\Gamma \tag{5.10}
\]

where \( i, j \) and \( k \) are summation indexes. Note that the matrix element \( E_{mn} \) is zero in cases where the basis functions do not overlap, i.e. if the nodes \( m, n \) are not part of the same tetrahedron. What remains in order to get the coefficients \( u_n \) is to solve a sparse linear system. This is done by Maxwell. More details on the mathematical aspects of the method are given in ref. [32].

**Iteration**

After a first approximation of the potential, Maxwell produces an error estimate based on gradient information from the numerical solution and refines the triangulation where the gradient of the numerical solution is large. The basic steps are iterated until a solution with a small error estimate is reached. If the convergence is too slow the iteration will be forced to stop when the number of tetrahedrons grows too large. We will see that this is often the case for the simulation described in this chapter.
Electric field map

Maxwell calculates a numerical potential field map built up from local quadratic polynomials. It then computes the gradient giving a linear electric field. It has to be remembered that the original error estimate and refinement of the mesh is based on the voltage map and not the electric field. Therefore the electric field map may have larger errors and show larger fluctuations than the original solution for the potential. A second remark is that the assumption of piecewise quadratic potentials has to be made with care in systems with large variations in scale. In the simulation treated below one encounters problems with thin wires, where the potential scales as $V \sim \ln(r)$ (cylindrical coordinates). The approximation of $\ln(r)$ fields as being piecewise quadratic is not optimal. It can be improved with a finer triangulation using the following method: One basic rule in triangulation implemented in Maxwell is that elements should never be allowed to cross a boundary surface since this would make the translation of material definitions and boundary conditions into the linear system very difficult (fig 5.3). By introducing fake surfaces in the chamber gas around the thin wire this rule forces the program to refine the mesh in the regions where the potential gradient is expected to be large. For a more detailed description of Finite Element Method the reader can consult resources on the WEB such as [29], [32] or[33].

5.1.2 Garfield

The final electric field-map provided by Maxwell can be loaded into the CERN developed program Garfield, where further simulations can be made. In this study the drift of electron and ions has been simulated, taking into account effects due to gas properties and magnetic fields.\textsuperscript{2} The gas data on which these simulations are based is the result of earlier simulation in Heed\textsuperscript{3}, Imonte\textsuperscript{4}, and Magboltz\textsuperscript{5}[34].

5.2 Strip structure

The active volume of the TPC is immersed in an axial electric field of 120 V/cm, in which ionization electrons drift towards the chamber. In order to obtain a constant drift velocity and a well understood, constant and minimized diffusion, the field should be as homogeneous as possible. The field

\textsuperscript{2}Argon 90% Methane 10%, atmospheric pressure, B=0.7 T

\textsuperscript{3}Heed is a program that computes in detail the energy loss of fast charged particles in gases, taking delta electrons, photo-ionization and multiple scattering of the incoming particle into account [35].

\textsuperscript{4}Imonte calculates electron transport and ionization processes in gases with a B-field [36].

\textsuperscript{5}Magboltz solves the Boltzmann transport equations for electrons in gas mixtures [36].
is generated by a constant potential surface at the downstream end of the TPC, a cathode wire plane in the chamber and two field cages shown in fig. 5.4 (where also the cylindrical coordinate system \( r, \theta, z \) of the HARP TPC is defined). The field cage of the simulation is a double layer strip structure with a pitch of 11 mm, attached to a stesalit\(^6\) barrel. From this geometry to the true design, a third layer of conductors has been added inside the dielectric, for reasons described in the chapter on the experimental setup. Field distortions and their effect on coordinate errors, will be described in detail below for one geometry and mentioned briefly for a few alternative geometries which later have been discarded for reasons of performance.

### 5.2.1 Simulation geometry

Close to the wall of the outer barrel, the cylindric geometry of the fieldcage is locally approximately flat (small curvature). This makes it possible to perform a simulation in two dimensions instead of three, which allows for a higher granularity of the simulation mesh. The field cage is a structure along \( z \)\(^7\) with a period of 11 mm. The four period region shown in figure 5.5 has been considered in this simulation. As indicated in the figure, the region

---

\(^6\)Stesalit is a dielectric fiber plastic produced by a Swiss company, Stesalit.

\(^7\)Coordinate system of fig. 5.4.
Figure 5.5: The simulation geometry and its relation to the coordinate system of fig. 5.4 is shown in the left picture. The drift paths of electrons in the field shown to the right was simulated in Garfield. Electrons created at an equipotential line were allowed to drift inside the problem region. The gas and magnetic field used are the ones chosen for the TPC. In the coordinate system of the simulation, the y-axis corresponds to the cylinder axis, the x-axis is along the radius of the cylinder, and the z-axis is parallel to the strips. Note the distortions of the tracks close to the outer strip plane at $x = 0.3$ cm.

is delimited by two surfaces with normal field, one surface with tangential field and the grounded outer barrel.

5.2.2 $\mathbf{E} \times \mathbf{B}$ distortions close to the field cage

The discrete structure of the drift chamber gives electric field inhomogeneities with non-zero radial components in the area near the strips. This radial electric field component exerts a radial force on the electrons. The axial B-field bends the radial drift component into a circular motion. At some point, as the electron moves along the strips ($\theta$-direction of the TPC coordinate system of fig. 5.4), the magnetic force component balances out the radial electric force. When this happens, the electron continues in the given direction along the strips.

From the equation of motion of an electron with charge $e$ moving in a medium with friction $\mathbf{F}_f = -K \mathbf{v}$ under the influence of electric and magnetic fields, the drift velocity vector is determined by

$$\mathbf{v} = -\frac{eE\tau}{m(1 + \omega^2\tau^2)}(\mathbf{\hat{E}} + \omega\tau[\mathbf{\hat{E}} \times \mathbf{\hat{B}}] + \omega^2\tau^2(\mathbf{\hat{E}} \cdot \mathbf{\hat{B}})\mathbf{\hat{B}}) \quad (5.11)$$
Figure 5.6: Simulating electron drift 4.4 cm along the cylinder axis, the drift time (left) and the RMS and double amplitude of the ExB-oscillations was found (right). The field mesh was created in Maxwell and the Monte Carlo simulation was performed in Garfield.

where \( \omega = eB/m \) and \( \tau = m/K \) [7]. For parallel electric and magnetic fields, the expression is reduced to \( \vec{v} = e\vec{E}/K \), i.e. a drift along the field lines at a constant drift velocity. A misalignment between the electric field and the magnetic field gives a velocity component in the direction of \( \vec{E} \times \vec{B} \), which in this case corresponds to the direction perpendicular to both the cylinder axis and the field distortion. The phenomenon is called the ExB-effect.

The mirror symmetry of the geometry about the strip axis, gives that the radial field distortions must be symmetric. Therefore, after half a strip period, the radial part of the electric field changes direction and so does the \( \vec{E} \times \vec{B} \)-direction, and the electron motion along \( \theta \) will be reversed. In this way, the radial electric field distortions will force the electrons to follow an oscillatory path, mainly in the plane parallel to the chamber surface. This effect is also observed in the simulation results in figure 5.5, where the electrons close to the field cage follow oscillatory paths. Simulation of a few other geometries showed that the undesired oscillations are larger with a single layer strip structure or with a structure with larger gaps between the strips.
5.2.3 Distortions in time and position

The oscillatory motion of the electrons gives longer pathlengths and therefore also longer drift times (figure 5.6, left). This effect is pronounced very close to the strip plane, but inappreciable already 0.6 cm from the wire plane, well before the active region. It must be noted that the drift time over the problem region should be multiplied by a factor of forty to get a representative value for the real geometry. Since the delay in the active region is below 10 ns in the simulation, the effect is smaller than 0.4 μs in the real detector.

The oscillatory path results in an error also in the transverse position. The sign and size of the error depends on the position where the electron was created. The RMS and the amplitude of the oscillations causing the transverse deviation are shown in figure 5.6 (right). We note that the RMS of the path is below 100 μm already 0.5 cm away from the strips. Since this error is well below the resolution of the TPC it can be neglected.

5.3 Sense wire support

The chamber is the sensitive region of the TPC, especially the region around the sense wires where they are strung onto support spokes.8 As described in chapter 3, it is around the sense wires that the ionization electrons are multiplied through avalanche processes. In order to obtain a high gain large electric fields are needed around the sense wires, introducing risks of sparks and corona effects.9 Any corona effect, even if local, is therefore particularly dangerous since this could make it impossible to operate the whole chamber. To avoid this scenario, extensive simulation and testing was performed before construction, to provide input to the geometry and composition of the spoke structure.

5.3.1 Straight angle approximation

In an idealised and simplified model, the sense wires are approximated to have a straight angle against the insulator spokes, and the cathode wire grid is approximated to be a plane at ground.10 The overall symmetry of this approximation is ideal for simulation. As shown in figure 5.7, the geometry has four perfect symmetry surfaces with tangential fields, and two surfaces at ground. The numerical solution obtained in this simplified model can give indications about the accuracy of the numerical method, the problems that

---

8A thorough description of the chamber part of the TPC, the wire structure and the support spokes can be found in section 4.9.3.

9In localized high field regions, the gas can ionize spontaneously. At ion de-excitation light is emitted which can be seen as a corona.

10The sense wires are in reality strung in an hexagonal pattern, and the cathode wires define a web with grounded wires, not a grounded plane.
Figure 5.7: A simple straight angle model of the sense wire support. There are symmetry planes with tangential fields between each sense wire, inside the spoke and far away from the spoke. The pad plane and the cathode wire plane are approximated as planes at ground.

may arise in convergence and the undisturbed field configuration around the sense wire.

Undistorted field map

The dielectric support cannot induce any field distortions in a straight angle model. This can be deduced from fig. 5.8 (where the field strength is centred around the same value inside the spoke as outside) but it is also a consequence of basic physics laws. Boundaries between media with different dielectric properties affect the normal component of the field leaving the tangential component unchanged. From symmetry arguments, one realises that there can be no field components normal to the support surface and hence no field distortions. One can therefore observe the field map from this model and draw conclusion about what we can consider as an unperturbed behaviour. A few elementary observations can be noted:

- The electric field is higher in the electron drift direction (the plane of the avalanche) than in the sense wire plane. This is expected, since in the avalanche plane the potential is zero at the anode wires, 1.5 kV at the sense wires and goes back to ground again on the pad plane, whereas in the plane parallel to the pad plane there are only symmetry boundary conditions.

- Close to the sense wires, the electric field should be approximately as in the cylindrically symmetric case, $E \propto 1/r$. In this region it makes sense to lower the statistical error by averaging the field on a cylinder around the wire, as has been done in figure 5.8.
Field near support, support of epoxy, 90 degree angle

$E \, [V/cm]$

$\times 10^3$

$E \, [V/cm]$

At 10 $\mu$m
At 17.5 $\mu$m
At 25 $\mu$m
At 32.5 $\mu$m
At 40 $\mu$m

Plotted at 17.46.50 on 14/08/00 with Garfield version 7.02.

Figure 5.8: The field map of the straight angle model (fig. 5.7) calculated in Maxwell, the field strength averaged over a few cylinders around the sense wire is shown above. Note that each level curve is centred around a a fixed value of the field. The x-axis follows the sense wire, with the origin in the middle of the spoke. The surface of the spoke is at $x = 0.3$ mm. Inside the spoke, oscillations of the field map indicate problems with convergence because of polarization effects.

Comparison with a free wire and a wire inside a tube

We recall, from chapter 3, that the electric field inside a grounded tube with a HV wire in the middle is

$$\vec{E}_{\text{tube}} = \frac{V_0}{\ln(R/r_0)} \frac{1}{r}$$  \hspace{1cm} (5.12)

Two limiting cases for the HARP TPC would be a tube very far away, say at $R = 1$ m, and a tube as close as the pad plane and the cathode wire plane $R = 5$ mm. Inserting those numbers and the wire potential, $V_0 = 1.5$ kV,
Figure 5.9: The field map of a straight angle model computed in Maxwell which provides field maps with piecewise linear $E$. The field values from Maxwell are represented by $\blacktriangle$. The field inside a tube at 1 m is shown as a red line (lower field) and the field map inside a tube at 5 mm radius is shown as blue line (higher field). The yellow line is a fit to data giving $E[kV/cm] = \frac{1065}{r[\mu m]}$. 

67
into equation (5.12) we obtain

\[
E_{\text{far}}[\text{kV/cm}] = \frac{1303}{r[\mu m]} \\
E_{\text{close}}[\text{kV/cm}] = \frac{2414}{r[\mu m]} \tag{5.13}
\]

Of course, neither of these two models describes the HARP geometry correctly, but it is expected to have field values somewhere in between. In figure 5.9, the field strength of the straight angle geometry, calculated in Maxwell, is shown together with the field of the two different models. Assuming a field roughly of the shape \( E \sim 1/r \), in the vicinity of the wire, the best fit to data gives

\[
E[\text{kV/cm}] = \frac{1565}{r[\mu m]} \tag{5.14}
\]

Conclusions about the simulation method

Numerical methods such as the quadratic FEM have difficulties dealing with problems involving scales over many orders of magnitude. In Maxwell, the potential is approximated as a piecewise quadratic function, and the electric field as a piecewise linear function. The problem of approximating a singularity like \( V \sim \ln r \) by a quadratic function or equivalently an \( E \sim 1/r \) dependence with a linear function is clearly demonstrated in figure 5.9. We conclude that it is important to have a fine mesh in regions with large field strengths, such as around the sense wire.

From figure 5.8 a second observation should be noted. The field in the region very close to the sense wire has an inhomogeneous appearance inside the dielectric support (\( x < 3 \text{ mm} \)). In this region there are difficulties with dielectric polarisation effects. The solution fluctuates more before convergence here than it does in the chamber gas outside the spoke. The conclusion is that it is also important to have a fine mesh in and around dielectric objects to correctly calculate polarization effects.

Simulation with conductive inserts

Profiting from the simplicity of the straight angle model, further simulations have been performed, examining the effects of conductive inserts. For future reference a few, intuitively reasonable, conclusions can be drawn:

- The electric field is reduced by adding conductors at high potential close to the sense wires.
- Hiding the high potential conductor inside the spoke, makes the reduction less pronounced.
- Varying the thickness of the HV conductor, has an effect on the field strengths. For thicker conductors the field reduction remains further away from the HV conductor.
Figure 5.10: In the TPC chamber the wires are strung on support spokes, in a hexagonal shape. This geometry gives a $60^\circ$ degree angle between the spoke and the wires. Two different models have been simulated, one with one wire and one with three wires. The regions are shown as hatched lines.

- The opposite effect can be obtained using conductors at low potential.

5.3.2 Sense wires at a 60 degree angle against the spokes

Conditions on dielectric boundaries

As explained in chapter 4.9.3, the chamber wires are strung on spokes in a hexagonal shape (see also fig. 5.19 below). In this geometry, as opposed to the straight angle approximation, there can be field components normal to the surface of the spoke. The boundary conditions for fields over dielectric boundaries are:

$$\Delta E_t = 0 \quad (5.15)$$

$$\frac{E_t(\text{gas})}{E_t(\text{die.})} = \chi_e \quad (5.16)$$

Where the electric susceptibility is $\chi_e = 4.5$ for the HARP TPC gas. As a consequence of the boundary conditions, the dielectric pushes large parts of the normal field components out into the gas. This phenomenon is called field ejection. In the region near the sense wire, where there are already high field strengths, field ejection can lead to sparks and corona effects, which should be avoided. Another less severe consequence of the boundary condition is that the field within the dielectric stays tangential to the dielectric boundary.
Figure 5.11: Maps of the electric field strengths around a wire entering a support at a 60 degree angle calculated using FEM. Two features of the three wire model (above) deserves to be noted: A lowering of the maximum field strength inside the support, compensated by an increase of the range. In the one wire model (below) these effects are less pronounced, indicating that there is indeed a change in the solution because of the extra symmetry assumptions introduced within this model. The smooth appearance of the one wire field map compared to the three wire map indicates that the accuracy is better in this model. The rod extends to 0.69 cm in the three wire model and to 0.46 cm in the one wire model.
Comparison between the one and the three wire model

For this geometry, two different problem volumes were defined, one with a single wire and one with three wires (fig. 5.10). The boundary conditions were set to be the same as in the straight angle model (fig. 5.7) with four symmetry boundaries and two constant potential boundaries. This is however an approximation, as opposed to the straight angle case. Now the surface between two wires is really a symmetry surface only far from the spoke and the spoke itself is not symmetric about this surface (see fig. 5.10). Since the spoke is a critical field shaping element, there is a risk that the assumption of mirror symmetry about this surface changes the problem and that the field map does not correspond to the true geometry. We expect a three wire model to be less affected by this than the one wire model, especially for the middle wire which is far from the symmetry boundaries. A comparison between the one wire model and the three wire model was made to check the error introduced by the symmetry assumption. In the field map of the three wire model (fig. 5.11) we observe a decrease of the maximum field strength inside the support, compensated by an increase of the range of the relatively high fields. In the one wire model these effects are less pronounced, indicating that there is indeed a significant change in the field map introduced by the extra symmetry assumptions in the one wire model. The three wire model has drawbacks as well: we are forced to use a lower granularity in the triangulation because of the larger simulated volume, making it hard to draw quantitative conclusions from the numerical map. From inspection of the three wire solutions we conclude that the method has not quite converged before reaching the maximum mesh size. The smooth shape of the one wire field map indicates that this model has converged properly. Since both of the models have advantages and drawbacks, the information from the two cases should be used in a complementary way.

Field ejection

In the field maps of fig. 5.11, it is hard to distinguish any high field areas near to the spoke. Hoping to increase the accuracy, the fields were averaged on cylindrical surfaces around the wire, the result of this operation is shown in figure 5.12. In the one wire model the field increase in the near wire/near spoke region is only marginally higher than the nominal field strengths, a few percent. In the three wire model these values are slightly higher, of the order of 10%. In this case the resolution is however pretty bad and it is hard to give any conclusive quantitative estimates. Maxwell does not provide a local error estimate for the user, even though the refinement of the mesh is based on such an estimate. The only indication about the local error in this region is given by how the mesh and the field map changes between iterations. The relatively stable behaviour during the iteration
Figure 5.12: The FEM field map from the three wire approximation (left) and the one wire approximation (right) averaged on cylindrical surfaces around a wire. The axis is along the sense wire, with the spoke extending to 0.09 cm in the three wire model and to 0.46 cm in the one wire model.

process leads us to believe that the field ejections are indeed limited to the 10% level. However, considering the low resolution in the three wire solution and the significant differences between the three wire and the one wire model, field ejection by the spoke can not entirely be excluded. Since problems with corona formation could seriously degrade the detector performance, we consider another geometry, to be on the safe side.

5.3.3 Hexagonal structure with HV supply line

Adding a high voltage supply inside the spoke would be a good idea for several reasons: It would (as will be shown below) suppress high electric field in the region where the sense wire enters the support. At the same time it would allow to rapidly restore the HV potential to the wire following a large avalanche.\textsuperscript{11} Therefore a 200 \( \mu \text{m} \) HV supply line in the middle of the support spoke was added to the model and a simulation was performed.

\textsuperscript{11}The resistivity of the sense wires is about 50 \( \Omega/\text{m} \), for a total of about 5 k\( \Omega \) over the full HARP wires length.
Figure 5.13: Maps of the field strengths in the vicinity of a sense wire found through FEM simulation. The sense wire enters the support at a 60 degree angle. Inside the support spoke there is a 200 μm HV supply line. The rod extends to 0.69 cm in the three wire model and to 0.46 cm in the one wire model. The smoothness of the field maps indicates that the method has converged to a stable behaviour. The difference between the one and the three wire model is therefore entirely caused by the extra symmetry surfaces in the one wire model.
Figure 5.14: The average field strength as a function of the distance from the spoke axis for different values of the radial distance from the sense wire. The model is an hexagonally strung sense wire going through an insulator support in the middle of which there is an 200 \( \mu m \) HV supply. The results is from a simulation with three wires, the dielectric spoke extends from \( x=0.35 \) cm to 0.69 cm.

The main electrostatic effect of the voltage supply is a reduction of the field close to the spoke (fig. 5.13).

Neither in the field map of the three wire simulation nor in the single wire simulation solution are there now any hints for high field regions near the spokes. The HV supply line shapes the field to a more smooth behaviour, which is reflected in a faster and better convergence of both field maps. With both models properly converged the differences can only be attributed to the introduction of the extra symmetry surface in the one wire model, with the three wire model expected to be more realistic. At this stage, we therefore choose to abandon the one wire model. A better statistical error is again obtained from averaging the electric field strength on a cylinder surface around the wire, giving a mean value calculated over several tetrahedrons. This procedure is only meaningful under the assumption that the field map is axially symmetric close to the wire, which is a reasonable assumption from inspecting the field map. The result of averaging for the three wire simulation is reported in figure 5.14. We note that the maximum
Figure 5.15: The Townsend coefficient $\alpha$ as a function of the electric field was obtained from an Imonte simulation of the avalanche process. The conditions were chosen so as to correspond to the HARP gas: 90% Argon, 10% methane at atmospheric pressure and 20 degrees. A linear fit up to $E=200$ kV/cm gives the relation $\alpha [k/cm] = 0.024[E[kV/cm] - 24]$.\[24\]

field strength is lowered, but never more than 15%. Moreover, the field strengths increase quickly with the distance from the wire, reaching undistorted values already after one pad width (7 mm). A last remark is that the effect of the supply line can be tuned, by changing the size and position of the wire as discussed for the straight angle model.

5.3.4 Expected gain losses close to the rods

We recall from chapter 3 that the gain depends exponentially on the integral over the Townsend coefficient as,

$$G = \exp \left[ - \int_{r(E_{\text{min}})}^{r_0} \alpha(r)dr \right] = \exp \left[ \int_{E_{\text{min}}}^{E(r_0)} \frac{\alpha(E)}{dE/ds} dE \right]$$

(5.17)

To obtain a high precision in gain, the precision in the Townsend coefficient and in the field strength must therefore be extremely high. It is therefore difficult to predict gain in non-ideal geometries. In the following we present an attempt to do this. To get a feeling for the gain that could be expected for
Figure 5.16: A numerical integration using the Townsend coefficient of equation $(5.18)$ and the electric field of figure 5.14 gives an estimate of the gain as a function of the distance from the surface of the support spoke. The avalanche was assumed to start at $E_{min} = 24 \text{kV/cm}$ and multiply exponentially until the charge was collected on the wire. The exponential dependence magnifies simulation errors, but the exercise still gives a hint on what changes in gains that could be expected in the near rod region. The fitted curve follows the relation $G = 108 \ln(x[mm] + 1.2)$.

the HARP TPC, the electric field of the limiting cases (equation $(5.13)$) and for the fit (equation $(5.14)$) is inserted into the Diethorn equation $(3.10)$. It is found, that the gain depends very sensitively on the field strength. From a difference in $E$ of a factor two between the limiting cases, there is a difference in gain with a factor 50, $G_{far} = 125$ and $G_{close} = 6027$. The fit gives $G_{fit} = 323$.

For gain estimates in perturbed regions, one use Monte Carlo simulation programs, such as the Imonte program [36]. Imonte calculates the avalanche process, taking into account electron attachment in the gas and secondary electrons. The Townsend coefficient as a function of the electric field was estimated for the HARP TPC using Imonte (fig. 5.15). A linear approximation in the region below $E = 200 \text{kV/cm}$ gives the relation

$$\alpha[k/cm] = 0.024(E[kV/cm] - 24)$$  \hspace{1cm} (5.18)

The linear fit was inserted into equation $(5.17)$, after which a numerical integration was performed using the field values from fig. 5.14. The minimum field for electron multiplication was taken from where the linear fit
Figural 5.17: In order not to break the thin sense wires, there is a small gap between sandwiched support structures. In this simulation model, the sense wires are held by a 200 μm dielectric knob.

crosses the x-axis, $E_{\text{min}} = 24$ kV/cm. From this operation a relation between the gain and the distance to the spoke surface was found (figure 5.16). The unhomogeneous behaviour of the gain estimate visualises how errors in $E$ and $\alpha$ are magnified in the gain. The gain was fitted with a logarithmic curve and, from the fit, the average over one pad was taken. Under the assumption that the field values are undistorted after one pad width, the gain reduction on the pad closest to the spoke was found to be 66%.

5.3.5 Sense wire holders design

The support structure was assembled in a "legolike" manner, with alternating support layers and wires (fig. 5.20). In this way the sense wire is mechanically sandwiched, in the z-direction between two layers of the support. A way to avoid breaking the thin sense wires would be to have a small empty space between the two insulators where the sense wires enter. Since they make a 120 degree angle at this point, the wires must of course be held: they are wrapped around knobs which can be made either from metal or from epoxy (for a schematic model see fig. 5.17). In fact, it is found from simulation that a metal knob causes considerable gain losses, for the same reason as already explained for the HV supply line (section 5.3.3). A dielectric knob also generates field distortions which are concentrated to the regions where the wire lies against the knob inside the gas gap, a region where large field ejections are observed (figure 5.18). This problem is however remedied by adding a HV supply line (see section 5.3.3).

5.3.6 Outer wheel

We recall that the sense wires are strung in an hexagonal shape around the spokes of the support “wheel” shown in figure 5.19. With a purely hexagonal stringing pattern, there will be space left between the last hexagon and the
Figure 5.18: The field map around a wire strung on a 200 μm insulator knob in a 1 mm gas gap inside the spoke. Note the high field regions generated by field ejection by the spoke. The left map shows the fields in the avalanche plane, and the map to the right shows the fields in the sense wire plane. The support spoke ranges from 0 to 0.3 cm.

outer wheel. To have this region sensitive, one additional sense wire per sector is strung in an S-shape directly on the wheel itself. The last section of this wire will be almost parallel to the outer wheel all along its length. In this region the dielectric wheel will polarize and generate a field increase around the sense wires. Simulation shows that a sense wire at a distance of 1 mm from an insulator wheel produces a field 40% higher than inside the sectors. This could again lead to the corona effects and sparking risks which we would like to avoid. Following the scheme of section 5.3.3 an HV guard ring is added on the inside of the outer wheel. For safety, a thicker last wire is also chosen. The guard ring and the thick external wire give gain reductions on the outer row. From the Diethorn formula for a free wire a gain reduction of a factor of two is found for the thicker wire, which is covering about a third of the pads in the outer row. For the rest, approximately the same reduction as for the pads by the spoke is expected giving an average signal reduction to about 80%.
Figure 6.19: The wire stringing pattern on the TBC wheel. One single wire is strung on the spokes of the wheel. When the spokes end, one wire per sector is strung in an S-shape on the outer wheel.
5.4 Complete wire support structure

The dielectric spokes also influence the drift of electrons before the amplification on the sense wires. To investigate possible distortions before amplification a simulation of the full wire support structure has been made. A schematic picture of the problem volume is presented in figure 5.21. The field map was computed in Maxwell and a good convergence was obtained. Monte Carlo simulation of the drift of electrons was performed in Garfield.

5.4.1 Dielectric spoke

A pure insulator spoke would be polarised in the 120 V/cm electric field inside the field cage. The polarisation would increase the potential close to the support, and generate field distortions. The field distortions would make electrons drift towards the support from the sides and some of these electrons would be absorbed on the surface of the dielectric spoke giving time dependent field distortions, so called charge-up. Other electrons would have their trajectories bent along the spoke radially; the \( E \times B \)-effect.\(^{12}\) The drift lines of electrons created on a line 2.5 cm away from the cathode wire plane, are presented in fig. 5.22. The field distortions introduced by the dielectric support would give big transverse deviations (\( \Delta r \sim 1 \text{ cm} \)) remain-

\(^{12}\)The \( E \times B \)-effect is explained in short in section 5.2.2.
**Figure 5.21:** In order to investigate drift distortions before amplification due to the support, a model of the spoke ranging from the cathode wire grid, past the gate wire grid and into the drift space was simulated. This is a schematic picture of the problem volume. A model with metal inserts is presented on the righthand side.

**Figure 5.22:** The plot shows the distortions of electron trajectories induced by a dielectric support without a guard ring. A large error in $r$ is introduced from $\mathbf{E} \times \mathbf{B}$-distortion in the region near the support. The electrons are created on a line 2.5 cm down stream from the cathode grid. The $z$-axis is parallel to the cylinder axis, the $x$-axis is parallel to the wires with a support ending at $x=3$ mm and the $y$-axis is radial. In this model, the support ranges from the cathode plane at $z=0$ past the gating grid at $z=0.6$ cm to $z=1.1$ cm.

**Figure 5.23:** A daring approach with two conductor inserts in the spoke, one just before the drift volume and one by the cathode plane. The conductors induce distortions in the electron trajectories, which can be tuned so as to give a small net error in coordinate estimates. The geometry of the simulation volume is the same as in the pure dielectric model to the left but a 2 mm metal slice (at -160 V) at the end of the support structure facing the drift space, and a second 1 mm metal slice by the grounded cathode plane was added.
ing several pad widths away from the support. The effect could be reversed by a conductive plate below the cathode grid at ground potential. However, such a configuration would most likely disturb more sensitive areas around the sense wires and is therefore not seen as an alternative.

5.4.2 Dielectric spoke with a guard ring

An electrostatically promising possibility is to add a conductive foil on the dielectric surface facing the drift volume. The foil would be put at the potential that would correspond to its position in the chamber. By totally covering the upper surface with a conductor there is no longer any surface of the dielectric where there is a normal component and hence no polarization. This ensures that the dielectric in no way can distort the field. The reasoning was confined by simulation.

5.4.3 Support with metal inserts

Another solution with high mechanical stability is to have thick metal inserts sandwiched inside the dielectric. This has been studied by the same technique already described and the conclusion is as follows: a careful choice of the conductor does allow to minimize the distortion in coordinate determination with a scheme of bending the trajectories in one direction and bending them back again. The electron trajectories in this configuration are presented in figure 5.23. Since another simulation has shown that the fully dielectric construction was mechanically stable, this more challenging option has been abandoned [37].
Chapter 6

Gain equalisation of the HARP TPC

From previous chapters (chapter 3 and 5) we recall that when an energetic particle traverses the TPC it knocks out electrons from the gas and that those electrons drift toward the TPC chamber and create avalanches around the sense wires.\(^1\) The ions created in the avalanche induce charge on the TPC read out pads\(^2\) which on average is proportional to the number of primary electrons. The proportionality factor, which is the topic of this chapter, is called gain. Due to instrumental effects such as wire sagging and electrical couplings between the wires and the support structure, the gain of the avalanche is expected to vary between different pad populations\(^3\). The induced signal is amplified once more by electronic means, differences in electronics amplification is expected to give an additional gain spread between pads. There are however several steps in the reconstruction chain which rely on information about the initial number of ionization electrons\(^4\), giving a need for a normalization of the raw digitized signals. This normalization is introduced by the concept of equalisation constants, which are pad specific gain norms putting the pads at an equal footing without connecting them to an absolute energy scale. In this chapter, methods to extract equalisation constants are developed and evaluated. The choice of data set, the gain measure used as equalisation constant, noise filtering, method stability and method validity will be discussed. The final result is an equalisation algorithm which is now applied in the HARP physics reconstruction software.

\(^1\)The avalanche process is described in section 3.2 and the sense wire configuration in 4.9.3
\(^2\)The induction is described in section 3.3 and pad plane configuration in 4.9.3.
\(^3\)Treated in chapter 5
\(^4\)For coordinate determination (clustering) and particle identification through the \(dE/dx\)-method, the charge of the recorded signal has to correspond to the number of primary electrons.
6.1 Data choice

Two different sets of data from the 2001 data taking period can be used for the equalisation: beam particle interactions, so called physics events\(^5\), and calibration. The read out signals from both data sets can be used not only to understand the reactions measured by the detector, but also to understand the detector itself. The first choice has been to use raw data as input for the equalisation, in order to reduce software biases in the equalisation process.

For beam particle interactions in the target, pads within the same row should collect approximately equal amount of charge on average. This is concluded on the basis of cylindrical symmetry of the phase space. The symmetry makes it straightforward to find relations between gains of pads within the same row. Care must be taken, however, since unprocessed beam particle data does not only contain tracks from interactions in the target. On the contrary, it contains signals from backscattering, δ-rays, beam halo interactions, non-interacting beam halo particles and signals due to neutron capture on the hydrogen of the gas (methane).

Another set of data is obtained from the cosmic ray calibration runs. It is cleaner than physics data in the sense that it has lower multiplicity, no target or inner field cage effects and less problems with secondary interactions and muon halo around the beam. The average cosmic ray event is a 4 GeV muon from above. At 4 GeV, the radius of curvature in the TPC magnetic field is of the order of 20 m which over the TPC gives a maximum sagitta of 4 mm. This is about the same as the raw resolution of the TPC, therefore the difference between the cosmic ray track and a straight line is negligible for equalization purposes. The cosmic ray data taking is triggered by combinations of RPC-barrel pads on opposite sides of the TPC.\(^6\) The cosmic ray distribution \(\frac{dN(r,\theta,\phi)}{dt}\) = \(\sin^2 \theta \sin^2 \phi\) combined with the trigger demand on diametral tracks result in a highly uneven illumination of the TPC pad plane as can be seen in figure 6.4. The horizontal sectors of the TPC are seldom covered by cosmic rays, which makes it hard to obtain enough statistics for the equalisation constants in these regions, an unavoidable drawback with the use of cosmic rays. Further details on properties of cosmic rays can be found in Appendix A.

6.2 Gain measure

The induced charge in a pad should, by definition, be proportional to the gain of the pad. The charge is registered through the current that flows onto the pad and amplified by the electronics chain before digitization and

---

\(^5\)A physics event need not necessarily have an interaction in the target, it is rather defined by the trigger condition. The trigger system is described in section 4.2.

\(^6\)Will be described in chapter 7
storage. The initial current time evolution follows an exponential shape, which is translated by the preamplifier into a gamma function\(^7\). The shape of the gamma function is entirely determined by electronics characteristics, and its amplitude is proportional to the charge on the pad. In a case where all preamplifiers give the same signal shape, the gain can in principle be obtained either from the signal voltage peak (\textit{max ADC}) or the integrated sum of the signal (\textit{sum ADC}). The digital sampling of the signal induces an additional uncertainty in the knowledge of the actual signal, disturbing the max ADC measure more than the sum ADC. This has led to the choice to use the charge as the weight of each signal in the reconstruction (clustering\(^8\)). Therefore this is the quantity that should be determined also by the equalisation.

The HARP TPC signals are unfortunately affected by cross talk. Cross talk can produce fake signals, influencing both the signal peak and the integral charge of the signal.\(^9\) These effects are under study and optimization is ongoing. With this in mind, it is reasonable to consider several different gain measurements to allow freedom of choice in the next steps.

### 6.3 Equalisation from physics trigger raw data

The first approach to extract a set of equalisation constants was to do unfiltered raw data analysis. Three different methods were investigated: the \textit{amplitude} method, the \textit{charge} method and a modified version of the charge method with a moderate noise cut. These methods will all be described and evaluated in this section. Using unfiltered raw data means treating all signals, that are neither caused by the gating grid\(^10\) nor the laser, as equal. A signal was defined as a current peak above threshold (10 ADC counts above pedestal) with a reasonable length (0.2-2 \(\mu s\)). In the amplitude method, the maximum ADC value of each signal was stored in a pad specific histogram. The signal amplitude distribution was found to be exponential in nearly all pads\(^11\). The same kind of exponential distributions were obtained also in the charge method, where the sum of the ADC read out was stored instead of the amplitude. Fitting an exponential,

\[
F(\text{ADC}) = \frac{L}{G} e^{-\frac{\text{ADC}}{G}}
\]

(6.1)

to the ADC readout distribution gives the mean, \(G\), and the luminosity, \(L\), on the pad from the fit parameters. The equalisation constant was in this

---

\(^7\)See chapter 4 on the experimental setup.

\(^8\)Treated in chapter 7

\(^9\)The work on, and the effects of, the cross talk will be discussed further in chapter 7.

\(^{10}\)When the TPC readout is triggered, the gating grid is opened by a change of the potential on the wires (see chapter 4). This process can induce a signal on the pad plane during the first micro seconds of readout.

\(^{11}\)This can be described by the Yule-Furry process from section 3.2.2
method defined as the value of $G$ given by the fit. A typical distribution, both for the maxADC and the sumADC case, is shown in figure 6.1. The goodness of the fit is indicated by the $P(\chi^2)$-distribution for the pad population (fig. 6.1). The group of pads with low $P(\chi^2)$ has been confirmed to be noisy pads whereas concentration of pads with high $P(\chi^2)$ most likely is due to error over estimation.

6.3.1 Monte Carlo simulation of the method

In order to investigate whether the method can correctly extract the gain of the pads, the following simulation was performed: Tracks of 1 GeV pions in the forward direction, with an opening angle $\theta < \pi/3$, where most tracks are found in fixed target experiments in the HARP energy range, were generated in Heed$^{12}$. The tracks are generated with Heed and the drift is simulated in Garfield.$^{13}$ When the electrons reach the sense wire each

---

$^{12}$Heed is a program that computes in detail the energy loss of fast charged particles in gases, taking delta electrons, photo-ionization and multiple scattering of the incoming particle into account [35].

$^{13}$For a short description of Garfield, see chapter 3.
Figure 6.2: Tracks for 1 GeV pions at opening angles uniformly distributed between -30 degrees and 30 degrees were generated in Heed. Each ionization electron from the track has induced an independent avalanche with an exponentially distributed multiplication factor with a known mean gain. Signals have been computed, digitised and convoluted with the HARP electronics transfer function, which is a gamma function. From each of these signals, the peak amplitude and the total ADC pulse height has been extracted and histogrammed. The high end tails of these distributions were fitted with an exponential of which the inverse slope is compared with the known gain.[24]
ionization electron induces an independent avalanche with an exponentially distributed multiplication factor with a known mean gain.\textsuperscript{14} The electrons have been treated as independent (proportional mode) and the summation over electrons has been performed at the level of ion density around the sense wire. The distance between the pad centre and the avalanche has been randomly distributed and the induced charge on the pad was given by the Gatti-Mathieson pad response function (fig. 4.14). The signal on the read out pad has been computed (an exponential with an area corresponding to the induced charge), convoluted with the HARP electronics transfer function (a gamma function), and digitized. The peak amplitude and the total charge has been extracted from each of the signals and histogrammed. Such a histogram is shown in figure 6.5. It is clearly not an exponential, but rather a Gaussian with an exponential tail, a difference which can be attributed to the fact that electronics noise was not included in the simulation. White noise is in general dominated by small signals and could fill the lower part of the distribution, whereas the upper part of the distribution could still come from track signals. In trying to simulate the equalisation algorithm operating on raw data, the high end tail of the distribution was fitted with an exponential, of which the inverse slope gave the equalisation constants. In fig. 6.2 the equalisation constant obtained in the Monte Carlo simulation is compared with the known gain. In the region with gains between 1000 and 10 000, the ratio between the equalisation constant and the known gain was found to be nearly linear, both for the amplitude and the charge method, leading to the conclusion that the method is sound when it comes to gain sensitivity.\textsuperscript{[24]}

6.3.2 Noise rejection

From comparison between simulated signal distributions and the distributions found from equalisation using raw data, the conclusion was drawn that a large fraction of the low charge/amplitude signals must be due to noise. In many cases there was indeed a kink in the signal size distributions, indicating that there could be two different sources to the signals: noise and particle tracks. Therefore a modified version of the charge method was explored. It treats small signals as though they contain no information and performs an exponential fit only in the region of large signals, similar to the method of the simulation. With this approach a third set of equalisation constants was obtained.

6.3.3 Validity of the method

After theoretically validating the three methods with the Monte Carlo simulation it turned out that in practice their application is not straightforward.\textsuperscript{14} Undamped amplification, see the Yule-Furry process treated in chapter 3.
The gain map obtained by any of the methods (charge or amplitude, whole distribution or upper part) varied rapidly with time, even on the relatively short time scale of one day. Another strong indication that the methods were not able to extract the true gain of the pads is that the equalisation constants were not related to the independent krypton calibration constants at all, and that applying the equalisation correction factors to the pad signals in krypton decay data did not lead to a higher resolution in the krypton decay spectrum.\textsuperscript{15} The conclusion is that blind TPC raw data processing is too sensitive to random noise, glitches in the electronics and cross talk to extract the gain of the pads.

6.4 Equalisation using filtered data

Another way of extracting equalisation constants is to use filtered data. One way of filtering out noise is to use only such signals that are known to come from particle tracks. To achieve this, clustering, pattern recognition and track fitting have to provide track parameters before the equalisation algorithm analyses the raw data. One has to keep in mind that this treatment introduces an additional risk for systematic errors from efficiency variations in the software chain, especially in the development stage when efficiencies and systematic effects are not known in detail.

The equalisation method described below is the one that is now being used for the HARP reconstruction. The first two steps of the track identification chain was to find points in space from raw data and to connect the points to a track. The two algorithms performing this task, clustering and pattern recognition, will be described in chapter 7. For all tracks that spanned more than 10 rows, the track parameters were found from a quadratic least square fit to the linear relations $z(x) = \frac{dz}{dx}(x - x_0)$ and $z(y) = \frac{dz}{dy}(y - y_0)$ where $z$ is the coordinate along the beam axis and $x$ and $y$ span the transverse plane. Parameters obtained from the linear fit, the range of the track and number of points in the track serve as input to the actual equalisation algorithm.

For a signal to be considered as physical (coming from a track) it is required that the pad centre should be closer than 1 cm from the track (in the transverse plane, see fig. 6.3). Since the pad response function has a width of 3.6 mm, very few physical signals should be cut away by this demand. An additional time window cut of $t_{\text{signal}} = t_{\text{rec}} \pm 1\mu s$ removes most of the random noise which is isolated in time from the track. The angle between the pad length axis (radial) and the track projection onto the pad plane also influences the signal. The TPC is designed for measuring tracks originating at the target, with an almost radial projection onto the pad plane. For almost radial tracks (small angle) the tracklength seen by

\textsuperscript{15}The krypton calibration is explained in section 4.11.3.
Figure 6.3: The display of clusters in a cosmic ray event. One cut used for filtering out noise is that the distance to the track in the transverse plane is less than 1 cm.

a pad increases giving larger signals. For very large angles the case is the opposite: the section of the track sampled by one pad is smaller resulting in smaller signals than for the radial tracks. Therefore the requirement \( \cos \alpha > 0.9 \) is put on the angle, \( \alpha \), between the track and the pad length axis. The charge of the signals that manage to pass the cut is stored in a pad specific histogram in the same way as the equalisation method of non filtered raw data described earlier.

6.4.1 Equalisation using cosmic ray data

The method described above was first tried on the clean sample of cosmic rays. As explained before they are close to straight lines (sagitta \( \leq 4 \text{ mm} \)) and no beam related background is present. A typical signal distribution is presented in figure 6.5. We note that there is a reduction in low energy signals (compare with figure 6.1) indicating that the method does indeed filter noise signals.
Figure 6.4: After clustering, pattern recognition and linear fitting on cosmic raw data with a trigger on diametrically traversing tracks a set of signals were identified as corresponding to cosmic rays. This is a colour map of the number of entries for each pad. The spokes, the inner barrel and dead and noisy regions are shown as empty patches. The red color is the high statistics end of the scale and purple the low statistics end. As can be seen from the colour codes cosmic rays give a highly uneven illumination of the pad plane.
Figure 6.5: The distribution of charge for one pad with a known gain obtained in a simulation (left) [24] and the distribution of the signal charge recorded in one pad with the method using filtered raw data (right). Signals were required to be in a time and space slot around a linear cosmic ray track.

6.4.2 Quality and stability

The central limit theorem states that the sum of many variables from any distribution always becomes a Gaussian at the limit of large numbers. This gives that the mean of the charge distribution should, for each pad, converge towards a fixed value when the number of entries increases. This value is the equalisation constant which approximates the gain of the pad. The standard deviation of this Gaussian is given from the rms of the charge distribution and the number of entries $N$ as,

$$
\sigma_{eq} = \frac{\text{rms}}{\sqrt{N}}
$$

(6.2)

which is therefore the error estimate on the equalisation constant. The gain is expected to vary slightly with temperature and pressure but to remain relatively constant over such short time scales as hours. This is confirmed by comparing equalisation constants obtained from two consecutive runs, as was done in fig. 6.6. The mean statistical error of the equalisation constants from each run is estimated to be about 10%, dominated by the high error tail from regions with low cosmic ray illumination. Since the time difference between the runs is only about 20 min, the true gain can safely be assumed
to have the same value for both runs. From the plot we can conclude that the method is stable within errors.

The properties of Gaussian distributions make it possible to test the method and the error estimates in another way. For variables $x$ and $y$ from Gaussian distributions, $x \in N(\mu_x, \sigma^2_x)$ and $y \in N(\mu_y, \sigma^2_y)$, where $\mu_x$ and $\mu_y$ are the means and $\sigma^2_x$ and $\sigma^2_y$ the variances, the following rules apply:

$$x + y \in N(\mu_x + \mu_y, \sigma^2_x + \sigma^2_y) \quad (6.3)$$

$$\frac{x - \mu_x}{\sigma_x} \in N(0, 1) \quad (6.4)$$

For two measurements of the equalisation constants for the same pad, $eq_1$ and $eq_2$ from runs close in time, equation 6.3 and 6.4 give

$$\frac{eq_1 - eq_2}{\sqrt{\sigma^2_1 + \sigma^2_2}} \in N(0, 1) \quad (6.5)$$
i.e the quantity on the left hand side has a normal distribution. The distribution of this difference for all the pads in the pad plane is shown in fig. 6.7. The centering at zero indicates that the gain can be assumed to be constant over the time range and the unit width indicates that the error estimates are sound. What still remains is to establish whether the equalisation constants are a good approximation of the gain.

6.4.3 Equalisation map

The equalisation procedure produces a map of the TPC read out pad plane with gain constants for each pad, which are presented in colour code in fig. 6.8. Each pad is represented by a coloured dot. The spectrum goes from violet, for low gains, to red, for high gains. The centre of the map not covered by pads is the shadow of the inner field cage. The six spokes on which the sense wires are strung can be distinguished as radial empty areas surrounded by low gain blue pads. Noisy or dead pads (which will be discussed in section 6.6) are considered blind and are represented as empty patches. From the plot one can see that the dead areas can be found as clusters on the pad plane. Such a group of dead pads are caused by a small number of badly soldered flexes. We note that noisy pads are generally found in groups of four inside a chip.\textsuperscript{16}

6.4.4 Sources of gain variations

In the gain map (fig. 6.8) groups of pads behaving in a similar way can be identified. One evidence is a gain reduction on the outer row compared to more central pads. Another feature is the trend of increasing gains in the centre of each sector for increasing radii and the most obvious is the gain decrease around the rods. Some of these features have been anticipated already in the electrostatic simulation (chapter 5), and can now be distinguished and quantified from real data.

Far away from support structures we would expect to find pads behaving in an undisturbed way. The distribution of nominal gains for this population is shown in figure 6.9(a). For pads close to the spokes (fig. 6.9(b)), these values are lowered considerably to a distribution with a mean gain reduced to 43\% compared to the undisturbed population. This is consistent with the prediction from electrostatic simulation that the reductions should be at least as large as 35\% (section 5.4.4). On the outer row the gains are also lowered, giving a distribution centred at 77\% (figure 6.9(c)). The semi-quantitative arguments in chapter 5.4 led to a prediction of gain reductions to about 70\%-80\%, which agrees well with this observation. The predictions as well as the observations from data are listed in table 6.1

\textsuperscript{16}The analogue electronics is described in chapter 4.9.3
Figure 6.8: A colour map of the TPC pad plane showing the effective equalisation constants from the cosmic ray equalisation method. The equalisation constants summarise the variations in gain, due to differences in the amplification around the sense wire and in the electronics between the various read out pads of the TPC. In the plot dead or noisy pads are shown as empty patches, high gain pads are red and low gain pads are blue, intermediate gains are described by the spectrum inbetween.
(a) Gain distribution for pads far away from support structures

(b) Gain distribution for pads close to spokes

(c) Gain distribution for pads close to outer wheel

**Figure 6.9:** In the ideal case the amplification of the ionization electrons around the sense wires would be uniform in the TPC. In reality the sense wires are spun on dielectric support rods with HV conductors in the centre. The nominal gain is shown in (a), with a mean normalised to one. For pads close to the spokes these values are lowered considerably to a distribution with a mean of 0.43, (b). At the utmost pads the sense wire is parallel and close to the outer wheel, to protect the TPC from discharges a HV supply is strapped around the outer barrel which lowers the gains on the outer pads to a distribution with mean 0.77, (c).
<table>
<thead>
<tr>
<th>Population</th>
<th>Mean gain</th>
<th>RMS(gain)</th>
<th>Predicted gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unperturbed pads</td>
<td>1</td>
<td>0.237</td>
<td>1</td>
</tr>
<tr>
<td>Pads by spokes</td>
<td>0.43</td>
<td>0.2078</td>
<td>&lt;0.7</td>
</tr>
<tr>
<td>Pads on outer</td>
<td>0.77</td>
<td>0.2263</td>
<td>0.7-0.8</td>
</tr>
</tbody>
</table>

*Table 6.1: Gain variation for populations of pads in the pad plane*

Apart from the geometric differences leading to the division of the pad into the groups treated above, there are also instrumental differences in electronics, for example within the preamplifiers. This gives an additional width in the gain distribution for each population. The fact that the RMS of the gain distributions for the different pad subsamples are so similar, suggests that this width corresponds to the intrinsic width of the gain variations due to electronics.

### 6.5 Comparison with krypton calibration

For the calibration of the TPC, which connects the signal size in a pad to an absolute energy scale, a technique using the krypton spectrum is implemented\(^{17}\). This technique has been developed concurrently with the equalisation algorithm described in this thesis. Also the krypton calibration algorithm has provided a set of calibration constants for the pads. By calibrating the pads with either set of constants and compare the resolution of the krypton decay energy spectra, an independent cross check is possible. During the development a clear convergence towards agreement between the two methods has been observed. The correlation between the two data sets with error levels of the order of 4% in the cosmic ray calibration and 1% for the krypton set is presented in figure 6.10. The main difference is concentrated to the outer row where the normalised gain of the krypton method is only 80% compared to the krypton equalisation. This is presumably caused by cuts suppressing low energy signals applied in the krypton calibration. There are a few other differences between the two data sets that deserves to be mentioned. The cosmic rays traverse a pad radially at large opening angles giving a linear electron density of about 40 electrons per cm (at an energy of about 2 keV/cm). Such a typical cosmic ray event is shown in figure 6.3. The krypton is instead spread uniformly over the TPC giving a homogenous illumination of the TPC pad plane (fig. 4.18) at much higher energies. The energy of one cluster is in the energy range of 10-40 keV, originally deposited in one point in space. The energy spectrum of krypton decay within the TPC expressed in calibrated or equalised ADC counts are shown in fig. 6.11 and 6.12. The 41.6 keV peak is slightly sharper for the krypton calibration, but both calibration sets sharpens the spectrum. [38]

\(^{17}\)See chapter 4.11.3 for details.
Figure 6.10: Comparison between the calibration constants from the krypton calibration and the cosmic ray calibration.

6.6 Noisy pads

Apart from extracting the pad gains, the equalisation algorithm finds and labels malfunctioning channels. Out of the 3972 read out pads in the TPC pad plane, there are about 200 pads which never give a signal. These dead pads break the symmetry of the pad plane and must be identified for an unbiased track reconstruction. Fortunately they are easily identified just by looking at the raw ADC output. There is another population of malfunctioning unstable pads with a signal slowly varying up and down. Such low frequency signals are sampled and stored just like normal signals, only that the signal length and abundance take up large space on tapes and time during reconstruction and analysis of the data. The noise signals, if undetected, will give a set of unphysical signals. It is therefore important to identify these noisy pads and suppress them. Studies of the raw ADC signals show that this population is dominated by unstable baseline pads, with mean signal lengths much longer than 25 ADC time samples (2.5 $\mu$s compared to normal signals which are less than 1.0 $\mu$s). Another set of noisy pads, which do not pose as big a problem, give short random signals because of glitches in the electronics. These were identified through the large fraction of signals not corresponding to a track point, the so called fire ratio. The cuts, tuned to identify the unstable baseline population and the worst
Figure 6.11: The krypton decay spectrum obtained from the HARP TPC calibrated with the krypton calibration constants. The width of the 40 keV peak is about 5.55 keV.

Figure 6.12: The krypton decay spectrum obtained from the HARP TPC calibrated with the cosmic ray calibration constants. The width of the 40 keV peak is approximately 6.3 keV.

cases of the pads showing glitches, are a mean read out length larger than 2.5 µs and a fireratio larger than 80%. This gives a population of 145 noisy pads which are blocked from reconstruction, a filter which is now applied in the HARP reconstruction. The distribution of the fireratio versus the mean read out length during a cosmic ray run is shown in figure 6.13. Over a time period of days there is a migration between the noisy population and the pads behaving in a normal way. After this analysis, the unstable base line pads have been identified as pads over which the supply current is provided by two different voltage supplies instead of one. There are about 200 such potentially noisy pads, which have been recabled before the data taking period of 2002. This has been confirmed to eliminate the problem of unstable base line pads.
Figure 6.13: The distribution of fire ratio and mean signal lengths for the read out pad plane in the HARP TPC during cosmic ray data taking in November 2001. The fire ratio is defined as the fraction of events in which the pad fires without being on a track, the mean read out length is computed over the physics time window for all events where the pad fires.
Chapter 7

Reconstruction of particle trajectories in the HARP TPC

The aim of the software reconstruction chain is to transform raw detector information into particle information, such as the particle trajectory, momentum and identity. This chapter describes the principles and performance of the TPC reconstruction package as of April 2002. At that time the basic steps of the software reconstruction chain was implemented and tuning of the algorithms gave a fast increase of resolution, noise rejection and track finding efficiency. Reconstructed data of cosmic rays and secondary particles in proton collision on tantalum targets ($p_{\text{proton}}=3$ GeV/c) will be presented and briefly discussed.

7.1 The TPC reconstruction package

The TPC reconstruction package consists of a sequential set of algorithms mapping raw detector information into ionization clusters, ionization clusters into tracks, and tracks into particle information. The first link in the reconstruction chain is the equalisation algorithm which normalizes the ADC signals, it is described in detail in chapter 6. The second step is the clustering which maps the equalised ADC signals onto a set of points in space, so called clusters. The pattern recognition links these points into tracks and particle information is obtained from the helical or linear fit to the tracks. The principles and performances of the clustering, the track finding and the helical fit will be described below.
Figure 7.1: The spherical coordinate system \([r, \theta, \phi]\) defined with respect to the HARP TPC. The origin is at the target.

### 7.1.1 Clustering

The clustering algorithm uses the equalised ADC signals to find clusters on the particle tracks\(^1\). A single cluster is expected to give signals in two or three pads in a row\(^2\). Such signals are formed into groups by the clustering if the pads are nearest neighbours in a row (or neighbours separated only by masked dead or noisy pads) and the signals are overlapping in time.[40]

### Cross talk

During analysis and calibration of the HARP TPC signals some anomalies have been observed: peculiar pulse shapes with long rising times or after-pulses\(^3\), asymmetric responses within the pad rows\(^4\), large cluster sizes and low resolution. These effects have been identified to be a result of cross talk within the multi-layer TPC motherboard. Ongoing analysis and measurement aims to reproduce the original physics signals through an a posteriori software correction.

Some features of the cross talk signal components have been identified during data analysis and are now used to adapt the reconstruction chain to a high performance:

- The cross talk signal is generally delayed in time with respect to the original signal, typically 250 ns.

---

\(^1\)The concept of clusters is presented in section 3.1.4.

\(^2\)See the TPC pad response function in fig. 4.14.

\(^3\)The electronic transfer function should be a gamma function (see section 4.10).

\(^4\)The equalised signal distribution within the pad row is expected to follow the symmetric Gatti-Mathieson shape (fig. 4.14).
Figure 7.2: A schematic picture of an ADC time series in one pad. The TPC signals are grouped in a row wise manner into clusters. The cluster position is given by the barycenter of the signals in the cluster, with the signal charge as the load weight. To filter away signals due to cross talk, the charge has been modified to contain only the charge of the signal before the peak [39].

- The amplitude of the cross talk component is typically about 10% of the original signal amplitude. The coupling can be both positive and negative, which means that for negative cross talk the cross talk signal negates the physical signal. At the limit of saturation the negation is total and the information lost [28].

Cluster position

To reduce the effects of cross talk, filtering cuts based on time information are applied in the signal selection. Late signals within a cluster, i.e. 350 ns after the first signal, are considered not to contain physical information but only cross talk and are therefore rejected. To determine the time of a signal one should use an estimate which is minimally affected by the cross talk, such as the time when the signal first exceeds 50% of its maximum value. This time \( t \) can be found from a linear fit between \( (t_{\text{thres}}, ADC_{\text{thres}}) \) and \( (t_{\text{max}}, ADC_{\text{max}}) \). From the signal time the \( z \) coordinate is found from the relation \( z = v_{\text{dri}} ft \).

The position of the cluster is obtained from the barycenter of the signals within the cluster with the signal charge as the load weight. In order to reduce cross talk effects, only the charge of the leading part of the signal is
Figure 7.3: The pseudo residuals in $\phi$ (left) and $z$ (right) for points in the linearly fitted cosmic ray track. The TPC point resolution is given as the width of the fitted distributions: $\sigma_\phi = 2.3$ mm and $\sigma_z = 4.5$ mm [28].

taken into account

$$Q_{\text{corrected}} = \sum_{t=t_0}^{t_{\text{max} \cdot ADC}} ADC_t$$

(7.1)

where $ADC_t$ is the ADC readout at time $t$, $t_0$ is the time when the signal first exceeds threshold and $t_{\text{max} \cdot ADC}$ is the time when the signal reaches its maximum amplitude (see fig 7.2). The treatment assigns a position in space and a total charge to each cluster. [40]

Point resolution

The point resolution (cluster resolution) is at present measured from the pseudo residuals of the points in a cosmic ray track. A linear fit to the data gives the pseudo residuals in the coordinates $\theta$ and $z$ (fig. 5.4), presented in figure 7.3. Assuming a Gaussian shape the width of the distributions give a resolution of $\sigma_\theta = 2.3$ mm and $\sigma_z = 4.5$ mm. For the nearly radial tracks of interest in the HARP experiment the radial resolution is non critical. Using the more advanced helical fit gives approximately the same pseudo residuals and works both for cosmic ray data and physics data.

7.1.2 Pattern recognition

The role of the pattern recognition is to use the points (clusters) identified by the clustering to find tracks. The first step in this procedure is to build links between the points and the second is to connect the links into tracks. Tracks close to the outer barrel are expected to have a larger separation
Figure 7.4: The TPC pattern recognition links the clusters into tracks. It starts with two points and searches for new points to add. The criterion for adding a new point to a track segment is defined by a truncated cone as in the figure given by a starting radius ($SR$), a forward acceptance ($FA$) and an opening angle ($\theta$).

than those closer to the detector axis. Links close to the outer barrel are therefore used as seeds in the connecting phase of the pattern recognition. In searching for a point to add to the seed link, the line between the two outer points is followed toward the TPC axis. The criterion for adding a new point is defined by a truncated cone such as the one shown in figure 7.4. The cone size is given by a starting radius ($SR$), a forward acceptance ($FA$) and an opening angle ($\theta$), all tuned to obtain the best performance. The cone is centered around the linear fit of the track segment (link) found up to that point. After adding new points to the track candidate the axis is re-fitted and the search continues iteratively. If the segment becomes long enough (at least six points) it is considered to be a track. Otherwise, it is rejected and the points will be used for another track candidate [41]. From simulated data with the present point resolution and at least ten points in each track, the track finding efficiency was estimated to be $98\pm0.5\%$ [44].

7.1.3 Helical fit

The helical fit operates on the track found by the pattern recognition extracting the track parameters, the particle charge and momentum. A circular fit is performed by minimization of a fourth grade polynomial in the plane transverse to the track axis [42]. The circle fit gives the transverse momentum $p_T$, the emission angle $\phi_0$ and the particle charge. A straight line fit on the surface defined by the helix gives the pitch angle $\lambda$ ($\lambda$ is the angle, $\theta$, between the particle direction and the beam axis in fig. 7.1) [43]. The overall momentum resolution has been determined by comparing the fit parameters of two arms of the same cosmic ray traversing the TPC.

5The particle direction at the point of closest approach to the beam axis.
Figure 7.5: Difference between the fitted parameters for two arms of the same cosmic ray, $\Delta \phi$ (left) and $\Delta \lambda$ (right). The angular resolution in the transverse plane $\Delta \phi_0$ is found to be 0.067 radians (3.8 degrees) and in the pitch angle $\Delta \lambda$ it is 0.022 radians (1.2 degrees).

From the width of the distributions (figure 7.5) the angular resolution in the transverse plane $\Delta \phi$ is 0.067 radians (3.8 degrees) and in the pitch angle $\Delta \lambda$ it is 0.022 radians (1.2 degrees). From the study of these cosmic ray tracks, at a momentum of 0.5 GeV/c, the momentum resolution $\Delta p/p$ was determined to be about 30%. With some tracks of poor quality rejected from the analysis, the acceptance level of the helical fit is about 90%.

7.2 Cosmic rays

For a first test of the reconstruction package the clean data set of cosmic rays was used. As discussed in Appendix A the most probable cosmic ray particle in the GeV range is by far the muon ($>99\%$) with a most probable energy of 4 GeV and an overall angular distribution roughly of the shape $\frac{dN_\mu}{dA} \propto \sin^2\theta \sin^2\phi$.

7.2.1 Trigger

The triggering system for cosmic rays is the RPC barrel surrounding the TPC.\footnote{The RPC barrel is described in section 4.4} It triggers the TPC readout whenever there is a simultaneous hit in two diametrical situated RPC chambers. The chambers are grouped into triggering units of two chambers on each side of the barrel, apart from two asymmetric units with two chambers on one side and one on the other (fig. 7.6). Each unit is sensitive for a range of angles and together they cover the
Figure 7.6: The barrel RPC cosmic ray trigger. Its 30 chambers are divided into eight trigger units, each consisting of two chambers on each side of the barrel, apart from two asymmetric units with two chambers on one side and one on the other. The triggering condition is a signal in at least one chamber on each side within a unit. We note that it is not possible to make a perfectly $\phi$-symmetric trigger with this setup.

entire momentum spectrum in $\phi$. The RPC barrel does not trigger on tracks with very low opening angles, $\theta$, the same tracks which are suppressed by the angular distribution of the cosmic rays. The RPC trigger efficiency for a given track inclination in the $\theta$-direction depends on the spatial position of the track. It is however possible to introduce cuts in the active TPC volume that make the acceptance uniform within a given range of track opening angles. A reasonable region for consideration would be $\theta \in [\pi/4, 3\pi/4]$. Introducing this angular cut on tracks restores the $\theta$-symmetry of the trigger albeit not the $\phi$-symmetry.

7.2.2 Angular distribution

The angular distributions of reconstructed cosmic rays recorded during one run in the coordinate system defined in fig. 7.1 is presented in 7.7. A cut has been introduced on both the angle $\theta$ and the TPC region considered to obtain an unbiased trigger. For a perfectly uniform trigger in $\phi$ and in $\theta$ in the region $\theta \in [\pi/4, 3\pi/4]$ the distributions would have the shape of the shaded regions in figure 7.8 as is the case for the distribution in $\theta$. The distribution in $\phi$ shows a peak structure manifesting the trigger efficiency variation with transverse angle.
Figure 7.7: The angular distribution of cosmic ray events in the HARP TPC, $dN/d\theta$ (left) and $dN/d\phi$ (right). The cut $\theta \in [\pi/4, 3\pi/4]$ has been applied to obtain a sample with a homogenous trigger efficiency in $\theta$. The trigger is however inhomogenous in $\phi$ as seen from the peak structure of $dN/d\phi$ (right picture).

Figure 7.8: The cosmic ray distribution obtained from a toy Monte Carlo (see Appendix A) $dN/d\theta$ (left) and $dN/d\phi$ (right). The outline of the graphs is the distribution without corrections for trigger acceptance and the shaded areas are the expected distribution with a trigger only for the region $\theta \in [\pi/4, 3\pi/4]$. Note that the distribution $dN/d\phi$ is the same as the distribution for $dN/d\theta$. 

108
**Figure 7.9:** The distribution of $p_T$ (left) and $p_L$ (right) for a thick Ta target exposed to a 3 GeV/c proton beam. Each figure contains three histograms: the lowest histogram is for negatively charged particles; the middle histogram for positive charges; the top histogram is the sum of the two. The scales are in GeV/c [44].

### 7.3 Proton collisions on Ta at 3 GeV

For the *large angle analysis* performed by the HARP collaboration during the first months of 2002, the focus was set on large angle tracks from 3 GeV/c protons impinging on tantalum targets. This analysis focused on the reconstruction of tracks in the TPC. To reduce background, tracks are extrapolated to the nominal beam axis and required to originate at the target position. In addition, the tracks are required to point to an RPC hit inside the trigger time window. These two criteria select largely overlapping samples (tracks inside the right time window and from the target). Cross checks shows that the background was at the 1% level. The momentum distributions of large-angle secondaries produced within a thick tantalum target are presented in figure 7.9. Positively and negatively charged particles are shown separately together with the sum. We conclude that the TPC and the reconstruction package works and has produced data which can be used for physics analysis.
Conclusions

This thesis had two main objectives: the simulation of the electrostatic design of the Time Projection Chamber and the gain equalisation of the Time Projection Chamber.

The specific aim of the electrostatic design was to pinpoint (and avoid) risks of corona formation or sparks and to minimize distortions while maintaining a high and uniform gain over the pad plane. The results of the electrostatic design simulations have been used to guide the construction of the Time Projection Chamber. The double layer structure of the field cage has been chosen since it was shown to give negligible coordinate determination distortions.

The design of the spokes of the wire support was the most critical item of the chamber, especially the region near the sense wires. The simulation indicated the region where the sense wire approaches the spoke as the most critical. It has been shown that the addition of a high voltage supply line in the middle of each spoke can suppress possible high field regions, at the cost of a moderate gain reduction. The high voltage supply line also eliminates risks in the area where the sense wires are strung on knobs. Similar simulations lead to the decision to add a high voltage guard ring on the outer support wheel.

The dielectric of the wire support structures also influence the drift of electrons in the field cage. It was predicted that a pure dielectric support would be polarized by the electric field of the drift space, leading to considerable distortions in relatively large regions. The simulation has shown that covering the surface of the wire support with a conductive layer entirely suppresses the polarization effect.

The equalisation constants are a measure of the gain on sense wires and of the amplification of the electronics, which are not constant over the pad plane. The equalisation of the Time Projection Chamber was performed with cosmic rays and proton interaction data. Several techniques have been studied. The one which is now applied for the reconstruction of the Time Projection Chamber uses track information from reconstructed cosmic rays to determine pad gain as well as to mark dead and noisy channels. The method has been shown to be stable within errors, whereas the gains themselves vary with time. The algorithm developed in this thesis has been adopted into the HARP Software system to be used for the physics analysis.
Acknowledgements

This study has been performed under the supervision of Dr. Piero Zucchelli, to whom I am very very grateful for friendly support and interesting physics insights. I would also like to thank the Swedish Research Council/TTA for financial support making the stay at CERN possible and CERN for providing funding for a prolonged stay. Some extra thanks also to my devoted proof reading father, to Aafke Kraan, to my examinator at Uppsala University Tord Johansson and to experiment colleagues and friends: Simon Robbins, Rob Veenhof, Gabriel Vidal Satjes, Silvia Borghi and Gersende Prior. And last but not least I’d like to thank the entire HARP collaboration for embracing me in the group and making me feel at home.
Appendix A

Cosmic rays

The Earth is constantly being bombarded by energetic particles and nuclei from space, called cosmic rays. Most primary high energy cosmic rays come from astrophysical sources outside our solar system and some originate in the sun, having been thrust into space by solar flares. The magnetised solar wind and the geomagnetic field affects the particle stream blocking the part of the spectrum with the lowest energy from reaching the earth. Thus, the intensity of any component of the cosmic radiation depends both on the location on earth and on the time of measurement. The particle composition, arriving to the upper part of the atmosphere from space, depends on the energy: in the energy range between several GeV to beyond 100 TeV, about 79% of the primary nucleons are free protons and about 14% are bound in helium nuclei and the rest are bound in more complicated nuclei.

In the Earth atmosphere, the primary cosmic rays interact with the air molecules, producing new particles, so called secondary cosmic rays. Before reaching the earth surface the secondary cosmic rays can reinteract, decay or scatter (figure A.1). The nature of these processes is difficult to analyse, but can be described numerically. The input is obtained from measurements of primary fluxes at the top of the earth atmosphere and the result is verified through comparison with secondary fluxes at sea level.

At sea level muons are the most abundant charged particles, most of them produced at high altitudes in the atmosphere. The intensity of vertical muons above 1 GeV/c (the mean energy of the muons are 4 GeV) is about $70 m^{-2} s^{-1} sr^{-1}$, which makes us expect about 30 muons per second crossing the TPC.\footnote{The TPC cosmic ray trigger is described in chapter 7.} For charged particles, we expect most of the cosmic rays to come from above. Indeed, the overall angular distribution of the muons (characteristic for 3 GeV muons) is $\frac{dN}{d\theta} \propto \cos^2 \theta^\prime$, where $\theta^\prime$ is the angle between the incoming muon and the vertical axis. Muons of lower energy follow a steeper angular distribution and higher energy muons follow flatter angular distributions. This is a consequence of the fact that low energy
Figure A.1: Energetic primary cosmic rays can interact with particles in the earth atmosphere. In this picture the first interaction is hadronic after which the charged pion decays weakly and the neutral pion decays electromagnetically.

muons from the sides travel so far in the atmosphere that they decay before reaching sea level. In the muon spectrum there are both positive and negative muons, the ratio $n_{\mu^{+}}/n_{\mu^{-}}$ is approximately 1.3 in the energy ranges from 250 MeV up to 100 GeV. This reflects the typical positive charge of the primary cosmic rays.

At ground level the second largest component of the cosmic radiation is of electromagnetic origin from meson decay. It consists of electrons, photons and positrons with a complicated spectrum that depends sensitively on altitude. The flux of electrons and positrons above 1 GeV is only $\sim 0.2m^{-2}s^{-1}sr^{-1}$. The flux of low energy electrons are much larger, but for the HARP cosmic ray data taking, the electromagnetic component is typically stopped by the solenoid magnet iron return yoke surrounding the TPC, and can therefore be neglected. [2]
A.1 Cosmic ray distribution in the TPC polar coordinate system

The shape of the cosmic ray distribution is given by

\[
\frac{dN(\theta')}{d\Omega} \propto \cos^2 \theta'
\]  

(A.1)

where \( \theta' \) is the polar angle against the vertical axis. The relation between this angle and the coordinate system \([r, \theta, \phi]\), defined in figure 7.1, is

\[
\cos \theta' = \sin \theta \sin \phi
\]  

(A.2)

Inserting this relation into the distribution A.1 gives

\[
\frac{dN(\theta, \phi)}{d\Omega} = \sin^2 \theta \sin^2 \phi
\]  

(A.3)

In order to obtain an unbiased cosmic ray trigger in \( \theta \) for some angular region we require \( \theta \in [\pi/4, 3\pi/4] \). The reason for this is explained in the section about the cosmic ray trigger, chapter 7. A small Monte Carlo program is used to introduce such a cut and to perform integrations giving \( dN/d\theta \) and \( dN/d\phi \). In the Monte Carlo program a random number generator produces uniformly distributed numbers \([\theta, \phi]\) in the range 0 to \( \pi \) describing the direction of a track. To obtain a uniform sampling of space, a weight of \( \sin \theta \) is introduced. The intensity of cosmic muons in the region around this track, \( dN(\theta, \phi)/d\Omega \), is given from equation A.3 and all values are stored in an ntuple. In this ntuple, cuts can be made and the “theoretical” cosmic ray distributions can be examined in desired projections. The distribution of \( dN/d\phi \), which is the same as the distribution for \( dN/d\theta \), can be seen as the outline of the graphs in figure 7.8. The distributions obtained with the cut \( \theta \in [\pi/4, 3\pi/4] \) are shown as shadowed areas in the histograms.
Appendix B

Neutrino physics

In June 1998 an important event in neutrino physics occurred: the SuperKamiokande collaboration reported strong evidence for neutrino oscillations in the atmospheric neutrino data. In April 2002 the SNO collaboration confirmed the claim based on additional observation of neutral-current neutrino interactions in the solar cosmic ray data. Hints of such evidence had actually already been reported from solar neutrino experiments during the preceding 20 years (Homestake, Gallex, Sage), but it was not until the SuperKamiokande claim that the significance was indisputable. The phenomenon of neutrino oscillations imply non-zero neutrino masses and mixing between generations. This is investigated in many contexts: by observing atmospheric neutrinos and solar neutrinos, by accelerators, reactors and nuclear decays.

B.1 Solar neutrinos

The Solar Standard Model (SSM), developed and tested during the past 20 years, is the most precise description of processes in the sun. Among other observables, the SSM predicts the solar neutrino spectrum shown in figure B.1 as the result of several nuclear fusion processes believed to occur inside the sun. During the last 20 years several experiments, such as the Homestake experiment, Gallex and SAGE and most recently the SuperKamiokande experiment have found a lack of electron neutrinos as compared to predictions [46]. This has remained an unsolved puzzle until now. However, a recent measurement by the SNO experiment has shown that the solar neutrinos neutral current interactions, and therefore also the total flux of active neutrinos, matches the SSM expectations [45]. In figure B.2 the predictions of the total neutrino flux from the SSM is compared to the fluxes of electron neutrinos ($\Phi_e$) and non-electron neutrinos ($\Phi_{\mu\tau}$) matching the SNO neutral current ($\Phi_{NC}$), charged current ($\Phi_{CC}$) and elastic scattering ($\Phi_{ES}$) result. The conclusion is that the electron neutrinos must have undergone
Figure B.1: The solar neutrino spectrum as predicted by the standard solar model (SSM). The reactions are, from left to right: $pp \rightarrow d\nu_e, ^{13}\text{N} \rightarrow ^{13}\text{C} + \nu_e, ^{16}\text{O} \rightarrow ^{16}\text{Ne} + \nu_e, ^{17}\text{F} \rightarrow ^{17}\text{O} + \nu_e, ^{8}\text{B} \rightarrow ^{8}\text{Be} + \nu_e$ and $^3\text{He} \rightarrow ^4\text{He} + \nu_e$ referred to as $\text{hep}$. The spectral lines correspond to $^7\text{Be}^- \rightarrow ^7\text{Li}\nu_e(\gamma)$ and $2\nu_e^- \rightarrow d\nu_e$ referred to as $\text{pep}$. The shaded regions indicate the ranges of sensitivity for the Gallium, the Chlorine and the SuperK experiments. The SNO experiment has the same region of sensitivity as SuperK [2].

oscillations, i.e. changed identity, on their way to Earth [45].

B.2 Atmospheric neutrinos

A primary cosmic ray interacting with matter in the upper layers of our atmosphere can induce a hadronic shower as the one shown in fig. A.1. The charged pions and muons in the hadronic shower will eventually decay into neutrinos through the reactions:

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu), \mu^\pm \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \nu_\mu (\bar{\nu}_\mu)$$

(B.1)

Naively one would expect two $\nu_\mu$ for each $\nu_e$ at energies where the muon has had time to decay in flight on the way to the earth surface. The energy spectrum of the two neutrino species is computed by Monte Carlo simulation which has many difficulties, such as the lack of knowledge on low energy hadron production. As mentioned in Chapter 1, the uncertainties of the
Figure B.2: Flux of $^8B$ solar neutrinos which are $\mu$ or $\tau$ flavour vs flux of electron neutrinos deduced from the three neutrino reactions in SNO. The diagonal bands show the total flux as predicted by the SSM (dashed lines) and that measured with the NC reaction in SNO (solid band). The bands for the neutral currents, charged currents and elastic scattering intersect at the fit values for $\Phi_e$ and $\Phi_{\mu\tau}$, indicating that the combined flux results are consistent with neutrino flavour transformation assuming no distortion in the $^8B$ neutrino energy spectrum [45].

estimated neutrino flux are of the order of 30%, whereas the uncertainties in the flavour composition are about 5% (error estimate in the ration $\nu_\mu/\nu_e$). The double ratio

$$R = \frac{(\nu_\mu/\nu_e)_{measured}}{(\nu_\mu/\nu_e)_{predicted}}$$

has by several experiments been found to have a value of about 0.6. The Super Kamiokande experiment has examined the ratio R as a function of the path travelled by the particle from the atmosphere. The result is shown in fig. B.3. They found that the flux of $\nu_e$ and $\nu_\mu$ from above correspond pretty well with predictions. However, in the flux from the other part of the globe, the $\nu_\mu$ component is reduced while the flux of $\nu_e$ still corresponds to expectations. These data can be explained under the hypothesis of neutrino oscillations from $\nu_\mu$ into $\nu_\tau$ [46].
Figure B.3: The zenith angle dependence of multi-GeV neutrino interactions from Super Kamiokande. The expectations for no oscillations is shown in the hatched region. The dotted line is a neutrino oscillation fit to data [46].

B.3 Coupling between oscillations and masses

In the minimal standard model the neutrino is postulated to be massless. Therefore the existence of neutrino oscillations (and consequently neutrino mass) is often seen as an indication of physics beyond the Standard Model. The phenomenon where a neutrino created with a given flavour can change and interact as another flavour neutrino is what we call a neutrino oscillation. This will be described briefly below. A more detailed account on the principles of neutrino oscillations and further references can be found in [2]. In the leptonic decay

$$W^+ \rightarrow l^+ \nu_l$$

of a $W$ boson, the charged lepton of flavour $l(e, \mu$ or $\tau)$ is accompanied by a neutrino of the same flavour $\nu_l$. It is the weak interaction that defines the neutrino flavour: the flavour states $|\nu_l\rangle$ are the eigenstates of the weak interaction Hamiltonian. Mass is in the standard model described by interaction with the Higgs field: the mass states $|\nu_m\rangle$, which have defined mass, are therefore the eigenstates seen by the coupling to the Higgs field. The mass basis need not necessarily be the same as the flavour basis. As is the case for quarks, the neutrino flavour states could instead be linear superpositions of mass eigenstates,

$$|\nu_l\rangle = \sum_m U_{lm} |\nu_m\rangle \quad (B.2)$$

where $U$ is the leptonic mixing matrix. The time evolution of a mass state is given by the Schrödinger equation, expressed in the rest system time ($\tau_m$)
we write:

\[ |\nu_m(\tau_m)\rangle = e^{-iM_m \tau_m} |\nu_m(0)\rangle \]  
(B.3)

The phase factor from this formula, translated to the laboratory system time \(t\) and position \(L\), is

\[ e^{-iM_m \tau_m} = e^{-i(E_m t-p_m) L} \]  
(B.4)

which for highly relativistic particles such as neutrinos, for which \(L \approx t\) and

\[ p_m = \sqrt{E^2 - M_m^2} \approx E - M_m^2 / 2E, \]

can be rewritten as

\[ e^{-i(M_m^2/2E)L} \]  
(B.5)

Applying the time evolution phase shift for each mass state, the neutrino created as a \(\nu_i\) will after a distance \(L\) have evolved into

\[ |\nu_i(L)\rangle \approx \sum_m U_{im} e^{-i(M_m^2/2E)L} |\nu_m\rangle \]  
(B.6)

In this step it has been assumed that each mass state has a definite energy, the energy of the initial neutrino. From inversion of the unitary leptonic mixing matrix the combination of neutrino mass states can be expressed as a combination of flavour states as

\[ |\nu_i(L)\rangle \approx \sum_{\ell} \left[ \sum_m U_{im} e^{-i(M_m^2/2E)L} U_{\ell m}^* \right] |\nu_{\ell}\rangle \]  
(B.7)

Translation of this formulation to a probability of an oscillation gives

\[ P(\nu_i \rightarrow \nu_{\ell}; L) = |\langle \nu_{\ell} | \nu_i(L) \rangle|^2 = \left| \sum_m U_{im} e^{-i(M_m^2/2E)L} U_{\ell m}^* \right|^2 \]  
(B.8)

From the formula we note that oscillations are possible only if the free Hamiltonian eigenstates have masses and then only if the masses differ. A second requirement for oscillations is that the mixing matrix \(U\) must be non trivial.
Appendix C

HARP Software package

C.1 The HARP Software environment

The HARP software environment has an object orientated design, implemented in C++. It is divided into design elements called packages, highly related within themselves but loosely coupled to each other. Each package has a specific task defined a priori by user and software requirements [11].

Some packages related to the analysis performed in this masters thesis are:

- ObjectConv - decodes and objectifies raw data from binary files.
- HarpEvent - is a library with classes that can be handled by the transient event store, meaning that they can be transmitted from one algorithm to another, also between packages.
- HarpUI - is a ROOT\textsuperscript{1} based event display which can be used for data quality checks during data taking and debugging of analysis tools.
- HarpDD - the harp detector description, containing, for example, calibration and alignment procedures.
- Reconstruction - handles processing of raw information from the sub-detectors. It is in this package that the TPC reconstruction chain resides: equalisation, clustering, pattern recognition and track fitting.

Apart from software and analysis tools developed within the HARP collaboration, several commercial software libraries supported by CERN or developed at CERN are exploited[18], including:

- GAUDI - is the common framework for all HARP software components [50].
- OBJECTIVITY - is the database for storage and retrieval of data offline and online.

\textsuperscript{1}ROOT is a graphical analysis tool based on the programming language C++[49].
• GEANT4 - handles simulation and detector geometry representation.
• DATE - for data acquisition and monitoring.
• ROOT - event display and analysis tool
• LabView - for detector control.
• CVS and CMT - code management
• CLHEP - general classes useful for high energy physics

C.2 GAUDI

GAUDI is a framework under development for the CERN experiment LHCb and the version used by HARP is an adapted version sometimes referred to as Gaudino. An application within this framework contains but a small amount of code necessary to start up GAUDI and read a jobOptions file. In the jobOptions file one is able to specify the mode of operation of the program. Here one finds a listing of the libraries needed, the algorithms in the libraries that should be executed, their respective order and their input parameters. Here there is also a definition of the analysis dataset, the message level (verbosity) of the different algorithms and the output file. Only at run time are the libraries loaded and searched for the specified algorithms. GAUDI handles many aspects of the execution of an application: it processes the jobOptions file, it handles the loading of libraries at run time, the event loop control, the message service, the histogramming and ntuple service and memory stores. The executables called by GAUDI have to conform to a specific design, defined in the class Algorithm from which the executable algorithms inherit. Therefore all algorithm classes contain three mandatory member functions for initialisation, execution and finalisation. After startup GAUDI calls the initialisation member function of the algorithms (in order), retrieves the first event on the list from the database and start the event loop. In each loop an event is retrieved from the database and the execution member functions of the algorithms are executed. After the last event has been processed, GAUDI calls the finalise algorithms after which it stores and closes ntuples and histograms [48].

C.3 Equalisation code

The equalisation code was written in the Reconstruction package, where access is allowed to TPC raw data and partly reconstructed units such as clusters, hits and tracks. Once the methodology of the equalisation had been found and validated, parameters had to be tuned to give the desired performance. This work has been done in the physics analysis and visualisation program ROOT. The output of the equalisation procedure, used by the calibration algorithms, is an ASCII-file listing the gain of each pad and the reference gain, together with dead or noisy pads. Since different parts of
the readout electronics respond differently to temperature changes neither the set of noisy pads nor the equalisation constants are really constant over long periods of time. Therefore the equalisation is performed at frequent intervals, so that an equalisation file that is up-to-date can be used for any analysis.
Bibliography


http://www.cern.ch/Physics/ParticleDetector/BriefBook/


http://harp.web.cern.ch/harp/Classified/Sub_detectors/TPC


127


[15] Status Report to the SPSC, Presentation by Lucie Linssen for the SPSC the 31 October 2000,

[16] Status report of the HARP experiment, CERN-SPSC/2001-031 SPSC/M 672, 29 October 2001

[17] Harp Status Report, Presentation by Piero Zucchelli for the SPSC the 30 October 2001,


[20] RPCs for HARP TOF Beam Test Results of First Prototypes, HARP internal note, 11 September 2000, V. Ammosov et al.


[22] The web page of the HARP target group
http://www.shef.ac.uk/~phys/research/hep/harp/targets.html

[23] The web page of the HARP trigger group
http://harp.web.cern.ch/harp/Classified/Sub_detectors/Trigger/

[24] Calculation for the HARP-TPC readout
http://r.home.cern.ch/r/rjd/www/Harp/


[26] Use of Krypton-83 as a Calibration Source for the STAR TPC Yale Relativistic Heavy Ion Group, B. Lasiuk and C. A. Whitten
http://star.physics.yale.edu/users/lasiuk/docs/ps/kr-83.ps

[27] Gersende Prior, private communication

[28] Gabriel Vidal Satjes, private communication

128
[29] Introduction to Finite Element Methods (ASEN 5007) - Fall 2001, Department of Aerospace Engineering Sciences, University of Colorado at Boulder
http://caswww.colorado.edu/courses.d/IFEM.d/Home.html


[31] Maxwell is provided by ANSOFT. The web reference to ANSOFT is
http://www.ansoft.com/home2.cfm


[33] http://beatrice.gsf.de/~mperzl/papers/phd/felement.html

[34] CERN Write up, Simulation of gaseous detectors, Rob Veenhof
http://consult.cern.ch/writeup/garfield/

[35] Heed 1.01 has been developped by Igor Smirnov at CERN. The Heed 1.01 Write-up web resource can be found at
http://consult.cern.ch/writeup/heed/


[37] Anders Angantyr, Deformation of the HARP TPC wheels, Technical Note, CERN/TA1/00-06

[38] Alberto De Min, private communication

[39] TPC Clustering Status Report and Performance, Silvia Borghi, Presentations at HARP collaboration meeting 19 March 2002

[40] Silvia Borghi, private communication.

[41] Simon Robbins, private communication.


[44] Status report of the HARP experiment, CERN-SPSC/2002-019, SPSC/M 685, 10 May, 2002

[45] Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory, Q.R. Ahmad, 19 April 2002

129
[46] Study of neutrino oscillations with a low energy conventional neutrino super beam, Mauro Donegà, Università degli Studi Milano Anno Accademico 1999-2000


[49] The ROOT web page
http://root.cern.ch/root/Welcome.html

[50] The GAUDI web page
http://lhcb-comp.web.cern.ch/lhcb-comp/Frameworks/Gaudi/