Chapter 2
Silicon Vertex Detectors and Particle Identification

The ability to reconstruct the decay vertex of a b-hadron and simultaneously to know the type of particle associated with this vertex were the essential tools of inclusive b-physics at LEP. The demands of an ever more ambitious b-physics program at LEP (and also at the SLC) were the driving force behind the rapid development of silicon strip detectors capable of operating in the challenging environment of a collider. At the same time ‘traditional’ particle identification techniques such as ionisation energy loss \( \frac{dE}{dx} \) were being supplemented with radical new methods such as Ring Imaging Čerenkov Counters in order to give a particle identification capability at a level and scale never before attempted.

2.1 Silicon-Strip Vertex Detectors

Silicon strip detectors are able to detect the trajectory of charged particles so precisely that tracks extrapolated through the silicon hits and into the radius of the LEP beampipe, were able to resolve the quite complicated decay vertex topology of b-hadron decays. This is well illustrated by Fig. 2.1 which shows a candidate \( Z^0 \to bb \) event reconstructed by the ALEPH tracking and calorimetry sub-detectors. Two further views provide a close-up of how tracks reconstructed in the outer tracking volumes match with hits in the silicon and the lower view zooms in on the interaction region showing how the extrapolated tracks meet at vertex points. The excellent precision separates clearly the primary \( Z^0 \) decay vertex from three decay vertices, each associated with an error ellipse, which are likely to have originated from the decay of a \( B \) or \( \bar{B} \) producing a D-meson which itself decays some distance from the parent \( B \) into three tracks. Reconstruction of this type of topology would have been impossible with the relatively poor extrapolation resolution provided by the ‘standard’ tracking detectors of the LEP experiments e.g. drift chambers or TPC’s.

The physics of silicon-strip detectors has been extensively reported in the literature and will not be repeated here (for an excellent review, see e.g. [1]). Instead we will concentrate on those aspects of detector development which enabled the LEP b-physics program to function.
High energy physics experiments first used semiconductor devices in the 1970s to measure particle energies but it was not until the advent of the planar production technique of silicon $p$-$n$ junction diodes by Kemmer [2] in 1980, that such detectors could be used also to measure particle trajectories. By segmenting one side of the junction into thin strips, particle positions are located according to which strip(s) collected a charge signal. The basic idea behind these silicon-strip detectors is illustrated in Fig. 2.2. The spatial resolution is determined by the strip spacing or ‘pitch’, which would ideally be smaller than the width of the charge distribution released from the passage of an ionising particle i.e. $\mathcal{O}10 \, \mu \text{m}$. In practice strip pitches of between 20 and 50 $\mu \text{m}$ can be achieved but spatial resolutions better than the geometrical limit of $\text{pitch} / \sqrt{12}$ can be reached by reconstructing offline the ‘centre of gravity’ of the charge distribution. The planar technique also allowed the possibility of simultaneously processing many silicon wafers so increasing the production yield and lowering the associated costs.

Silicon strip detectors were used successfully in fixed target experiments in the early 1980s to study charmed particles but before their use was possible in a collider experiment a number of developments were needed.

Fixed target experiments had the advantage of essentially unlimited space outside of the beamline and so they were able to use large fan-outs connecting the small strip pitch of the detectors to readout electronics where the channel pitch could be 2–3 orders of magnitude larger. This configuration would be impossible in a collider experiment where as much as possible of the space around the interaction should be instrumented with active detectors and the amount of passive material must be kept
to a minimum in order to limit the effects of multiple scattering on particle trajectories. It therefore became clear at an early stage that the density of readout channels would need to be much higher than was necessary in fixed target experiments and that detector engineering designs would be severely tested by space limitations and multiple scattering limits. Custom designed, Very Large Scale Integration (VLSI) ASIC’s were the technological breakthrough necessary to address these problems. Sub-5 μm feature processing enabled up to 128 readout channels to be crammed into an area of roughly 6 × 6 mm. The first example was the Multiplex chip, based on 5 μm NMOS technology, designed to readout the silicon strip detectors of the MARK II detector. The basic design of each channel, shown in Fig. 2.3, consists of a charge sensitive amplifier followed by two identical capacitor circuits one of which samples the charge before the arrival of the signal and the other after the signal has arrived. The voltage difference between the two is then proportional to the signal charge without the effects of noise (at least for noise with time variations much longer than the period between the two sampling times). This signal is stored and multiplexed onto a serial bus. The LEP experiments subsequently introduced their own variations on this original design which generally had much lower power consumption realised in 5 μm (or smaller) CMOS technology.

In collider-mode a significant fraction of particles cross the detector planes at low incidence angles which spreads the charge deposited over a number of readout strips. This reduces the size of particle signals and means that signal/noise performance of the detectors was much more of an issue for the collider experiments than was the case with fixed-target geometries. The main source of noise in silicon-strip detectors is often due to the capacitance of the strip being read-out, both to the back plane and to neighbouring strips. This causes signal loss and acts as a load capacitance to the channel amplifier which gives electronics noise. This can be minimised by making the coupling capacitance to the read-out electronics high and the inter-strip capacitance as low as possible. The bias resistor, through which the depletion voltage for the silicon substrate is supplied, is another source of noise which can
be kept under control by making the resistance as large as possible. Detectors were
developed that incorporated coupling capacitors (via SiO$_2$ layers) and poly-silicon
bias resistors (of a few $\times$ M$\Omega$) integrated in the detector silicon substrate itself. This
type of integration freed-up much needed space in the multiplex-chip designs and
helped to keep the amount of material through which particles must pass, down to
a minimum. The material budget is particularly important because of the multiple
Coulomb scattering it introduces and which limits the spatial resolution attainable
for low momentum tracks. The integration of more and more of the ancillary supply
and readout electronics onto the silicon wafer was a development that began with
the LEP detector designs and continues today in designs for the next generation of
detector.

An early development goal of the LEP vertex detector groups was to design a
strip detector that could provide 3D spatial points. This effort was pioneered by the
ALEPH collaboration who developed double-sided devices where the ohmic contact
(or n)-side of the device pictured in Fig. 2.2, was also segmented into strips running
in the perpendicular direction to the p-side strips. These devices are complicated
to manufacture and early production batches were of varying quality. Because of
this OPAL preferred the solution of sticking two single-sided devices, with perpen-
dicular strip orientations, back-to-back. Double-sided devices do however provide
the most satisfactory route to 3D reconstruction since the amount of material is
essentially no more than for single-sided devices and the correlation between pulse
heights collected on the $p$- and $n$-sides (so called, Landau correlations) can be used
to match signals from both sides with no ambiguity. For these reasons double-sided
development at LEP continued and in addition to ALEPH, double-sided sensors
were subsequently installed by DELPHI and L3. A comparison of the silicon detec-
tors of the LEP experiments is given in Table 2.1.

A very active area of development concerning double-sided devices, was how
to read-out the signals from the $n$-side strips which are oriented perpendicular to
### Table 2.1 Comparison of the silicon vertex detectors of the four LEP experiments in their final configurations

<table>
<thead>
<tr>
<th></th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. layers</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$\langle r_1 \rangle$ (cm)</td>
<td>6.3</td>
<td>6.3</td>
<td>6.1</td>
<td>6.2</td>
</tr>
<tr>
<td>$\langle r_2 \rangle$ (cm)</td>
<td>−</td>
<td>9.0</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>$\langle r_3 \rangle$ (cm)</td>
<td>10.7</td>
<td>10.9</td>
<td>7.8</td>
<td>7.7</td>
</tr>
<tr>
<td>No. detectors</td>
<td>96</td>
<td>288</td>
<td>96</td>
<td>75</td>
</tr>
<tr>
<td>Silicon area ($m^2$)</td>
<td>0.25</td>
<td>0.42</td>
<td>0.30</td>
<td>0.15</td>
</tr>
<tr>
<td>Readout-chip</td>
<td>CAMEX64A</td>
<td>MX3/MX6</td>
<td>SVXD</td>
<td>MX5/MX7</td>
</tr>
<tr>
<td>(3.5 $\mu$m CMOS)</td>
<td>(3 $\mu$m CMOS)</td>
<td>(3 $\mu$m CMOS)</td>
<td>(1.5 $\mu$m CMOS)</td>
<td></td>
</tr>
<tr>
<td>Signal/noise</td>
<td>17</td>
<td>13–16</td>
<td>−</td>
<td>22</td>
</tr>
</tbody>
</table>

The simplest scheme, implemented by ALEPH, is to mount read-out electronics directly at the end of the strips which has the disadvantage of introducing extra material. A preferable scheme is to read out both the $p$- and $n$-side strips at the ends of sensor modules away from the highest density of traversing particles. OPAL and L3 achieved this by routing the $n$-side signals to the end of modules by bonding to conducting lines laid down on glass (OPAL) and capton (L3) plates stuck directly onto the sensors. The most elaborate solution to this problem however, came from DELPHI who developed double-sided detectors with an extra, integral, metal layer to re-route the signals. These detectors, Fig. 2.4, represented the state-of-the-art in silicon strip detector design for collider experiments and presented many fabrication challenges for device manufacturers. Worth mention here also is the novel design choice of DELPHI to join neighbouring double-sided detectors in a ‘flipped’ configuration as shown in Fig. 2.5. Due to the biasing scheme chosen for the strip-devices, the readout lines on the $p$ and $n$-sides were at the same potential and it was therefore possible to bond the $n$-side readout lines of one detector to the $p$-side readout lines of the neighbouring detector. This arrangement was found to have a number of advantages [5] including an equalisation of capacitance noise from both sides, a signal polarity which tags cleanly which detector in the module produced the signal and some benefits for the alignment procedure which is discussed in Chap.3.

In parallel with developments in silicon-strip sensor design and read-out electronics, to make a multi-layer detector at the heart of a collider experiment presented many challenges for mechanical support structures, cable routing, multiplex-chip cooling etc. Spatial constraints were the main enemy and were particularly severe in the case of L3 and OPAL. Silicon detectors did not form part of the original Letters of Intent for these two experiments and were only possible after 1991 when the LEP beampipe radius was reduced from 8.5 to 5.5 cm. OPAL installed their silicon vertex detector in 1991 just one year after the project’s approval and L3 followed in 1993 2 years after approval. These rapid installation schedules pay testament to how rapidly all aspects of silicon vertex detector construction advanced in the early years of LEP. By 1994 all of the LEP experiments had working devices providing an intrinsic resolution of sub-10 $\mu$m in both the $R - \phi$ and $R - z$ planes. In order
to best exploit this resolution for physics required a careful alignment of the silicon detector modules and the optimisation of off-line reconstruction algorithms. These matters are discussed further in Chap. 3.

One further round of major modification to the LEP vertex detectors was triggered by the onset of the LEP 2 era where beam energy reached the 200 GeV...
2.2 Particle Identification

The LEP experiments were multi-purpose devices well equipped to detect and separate the stable products of $e^+e^-$ collisions: photons, electrons, muons, pions, kaons and protons. A broad range of, mainly well-established, techniques based on detecting ionisation and excitation energy loss and time-of-flight were used. Electromagnetic calorimeters reconstructed electron and photon-induced showers and hadron calorimeters performed the same function for hadronic showers. Muons could be identified by associating tracks with hits in the muon chambers around the very outside of the detectors.

In this section we will briefly review aspects of particle identification at LEP which were new or novel in some way and which played an important role in the b-physics program. This work in particular led to advances in how to combine particle identification information in an optimal way and this is discussed further in Chap. 3.


2.2.1 Specific Ionisation Energy Loss, $dE/dx$

Sampling the ionisation energy loss was an important technique for the ALEPH, DELPHI and OPAL experiments which were equipped with large tracking gas-chambers (diameter up to 3.6 m). The challenge at LEP was to attain sufficient resolution in the momentum range of interest i.e. $p > 1–2$ GeV, coinciding with the relativistic rise region of the Bethe-Bloch spectrum where energy loss differences between particle species are only of the order 10%. This is illustrated in Fig. 2.7 from OPAL which shows $\langle dE/dx \rangle$ measurements averaged over a maximum of 159 samples along the track length. To operate in the relativistic rise momentum region demands attaining resolutions on $dE/dx$ at the few percent level.

The large scale of the LEP tracking chambers were both an advantage and disadvantage to achieving the resolution needed on $dE/dx$. The advantage results from the fact that the measurement uncertainty, $\sigma (dE/dx)$, has the following inverse dependencies on the number of samples ($N$) and effective sampling length ($l = \text{thickness} \times \text{pressure}$): $\sigma (dE/dx) \propto N^{-0.43,-0.47}$ and $\sigma (dE/dx) \propto l^{-0.32,-0.36}$ respectively [9]. The disadvantage results from the practical difficulties associated with operating a stable and well understood drift chamber of this shear size. Gas purity, density and temperature all need to be carefully regulated and monitored to ensure charge gain is stable to the few percent level. For example, detailed non-linear corrections to the collected charge samples and rigorous quality cuts were needed in order to achieve the $dE/dx$ resolution of $\sim 3\%$ attained by the OPAL collaboration. Table 2.2 compares the parameters and performance of the LEP experiments.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig_2.7.png}
\caption{Measurements from OPAL of the mean energy loss $dE/dx$ of tracks in hadronic and di-muon decays of the $Z^0$. From [10]}
\end{figure}
Table 2.2 Comparison of $dE/dx$ performance of the LEP experiments. Resolutions are quoted for single isolated tracks and in hadronic events (parenthesis) if available. After [9]

<table>
<thead>
<tr>
<th></th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>[11]</td>
<td>[12]</td>
<td>[10]</td>
</tr>
<tr>
<td>Detector type</td>
<td>TPC</td>
<td>TPC</td>
<td>Jet drift chamber</td>
</tr>
<tr>
<td>Size ($\phi \times L$)</td>
<td>$3.6 \times 4.4$ m</td>
<td>$2.4 \times 2.7$ m</td>
<td>$3.6 \times 4.0$ m</td>
</tr>
<tr>
<td>Number of samples</td>
<td>338</td>
<td>192</td>
<td>159</td>
</tr>
<tr>
<td>Sampling length</td>
<td>4 mm</td>
<td>4 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>$dE/dx$ resolution (%)</td>
<td>4.5</td>
<td>4.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

2.2.2 Čerenkov Ring Imaging

Worth a special mention are the Ring Imaging Čerenkov (RICH) detectors of the DELPHI experiment. The principle idea is to measure the velocity of a particle which is travelling faster than the velocity of light in the local medium (with refractive index $n$) by measuring the Čerenkov light cone opening angle ($\theta_C$) and using the relationship $\theta_C = \frac{1}{nb}$. The velocity can then be combined with a measurement of the particle’s momentum from the tracking detectors in order to determine the mass and hence identify the particle type. By the 1980s, the technique was reasonably well established and had been used in a collider environment by the UA2 experiment for electron ID. DELPHI\(^1\) however proposed an altogether more sophisticated device consisting of a barrel and end-cap section each with a liquid ($C_6F_{14}$) and gas ($C_4F_{10}$, $C_5F_{12}$) radiator part able to separate $e$, $\mu$, $\pi$, $K$ and protons over a wide momentum range. Figure 2.8 illustrates the basic detection mechanism.

Figure 2.9 illustrates how the RICH detectors provide particle ID coverage from the relativistic rise region of the momentum range where separation of particle types by $dE/dx$ becomes difficult. By using liquid radiator to cover the region up to a few GeV/c and gas radiator for the higher momenta, DELPHI were able to have a particle ID capability over almost the full momentum range of LEP 1. Software tags for particle types can be defined simply by making cuts on the $dE/dx$ and RICH information depending on the purity and statistics of the sample required e.g. the efficiency for identifying $K^\pm$ averaged over the momentum spectrum above 0.7 GeV/c was about 70% with a contamination of about 30% while for protons the number was 70% efficiency for a contamination of 50%.

The stable operation and calibration of the DELPHI RICH was a huge technical challenge and many teething problems had to be overcome before the RICH data could contribute to physics results. A beautiful example of the power of a particle identification system containing a RICH capability is shown in Fig. 2.10. A candidate $B^- \rightarrow K^{0s}(892) + \pi^-$ decay is found in DELPHI by reconstructing the decay vertices in the silicon vertex detector and identifying the decay products with high probability by combining $dE/dx$ and RICH information.

\(^1\) Also, at about the same time, the CRID project of the SLD detector at SLAC.
2.2.3 Overall Detector Performance

Although there was considerable overlap in the designs, there were also significant differences between the four experiments. These differences reflected the desire to cover all possible physics channels optimally and to get the correct balance between
Fig. 2.10 A zoom-in view of the tracks extrapolated to the vertex region in the $x - y$ plane is shown in the upper plot where the $Z^0$ decay (lower right) and B decay (upper left) vertices are indicated by $3\sigma$ error ellipses. The plots below show the measured $dE/dx$ and RICH quantities for the decay products ($\pi^-$ plus $K^+\pi^-$ from the decay of the $K^{0}\bar{s}(892)$) overlaid on the curves expected for pions, kaons and protons. From [12]
Table 2.3 A comparison of the performance of the LEP experiments in their final configurations. After [17]

<table>
<thead>
<tr>
<th></th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-field</td>
<td>1.5T</td>
<td>1.2T</td>
<td>0.5T</td>
<td>0.435</td>
</tr>
<tr>
<td>σ (1/p) × 10^{-3} / √E GeV</td>
<td>(super cond.)</td>
<td>(super cond.)</td>
<td>(conventional)</td>
<td>(conventional)</td>
</tr>
<tr>
<td>σ(E) (Emag.)</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6(μ), 1.8(hadrons)</td>
<td>1.5</td>
</tr>
<tr>
<td>σ(E) (Hadronic)</td>
<td>0.18&lt;textarea&gt; ± 0.01&lt;/textarea&gt;</td>
<td>0.32&lt;textarea&gt; ± 0.04&lt;/textarea&gt;</td>
<td>0.02&lt;textarea&gt; ± 0.01&lt;/textarea&gt;</td>
<td>0.06&lt;textarea&gt; ± 0.02&lt;/textarea&gt;</td>
</tr>
<tr>
<td>R − φ IP resolution</td>
<td>25 μm</td>
<td>20 μm</td>
<td>30 μm</td>
<td>18 μm</td>
</tr>
<tr>
<td>R − z IP resolution</td>
<td>25 μm</td>
<td>30 μm</td>
<td>30 μm</td>
<td>20 μm</td>
</tr>
</tbody>
</table>

tried and tested technology over new developments in instrumentation. Examples of this include:

- The OPAL detector [13] design which was based on largely conventional technology and regarded as the ‘safe bet’ to fully function from day one of LEP operations.
- The ALEPH detector [14] with it’s ambitious silicon vertex detector with double-sided readout.
- The DELPHI detector [15] with the emphasis on state-of-the-art particle ID combining dE/dx sampling in a large TPC with RICH detectors.
- The L3 detector [16] optimised for electron and muon detection by including an electromagnetic calorimeter which was the first to use BGO crystals and all detector components sitting inside the world’s largest conventional 0.5T magnet.

The comparison of the performance attained by the LEP detectors is given in Table 2.3. The tracking spatial resolutions are quoted in terms of the impact parameter resolution and accounts only for the extrapolation error of the track back to the production point. Track impact parameter is discussed in Chaps. 3 and 4.

References

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