DATA ACQUISITION AND ANALYSIS AT LEP

J.V. Allaby
CERN, Geneva, Switzerland

ABSTRACT

LEP will be equipped with four experiments which are briefly described. Each will require a complex data acquisition system. The one being constructed for DELPHI will be used as an example, and described in some detail. Finally, the way in which the data is analysed will be reviewed, together with the ways that graphics techniques can play an important role in such analyses.

1. INTRODUCTION - WHAT IS LEP?

LEP is an electron-positron collider 26 Kms in circumference. Initially, four interaction regions will be equipped with experiments, although there is the potential for eight crossing points with four-bunch operation. Before reviewing the experiments, it is useful to recall some basic facts about LEP.

Figure 1: The Location of LEP.

The collider is located underground between the outskirts of Geneva and the Jura mountains (see Fig. 1). The major part of the tunnel in which LEP will be installed will be bored by machine in the "molasse" (a kind of sandstone) which lies at depths of several tens of metres below the surface of the
ground in this region, which is formed of glacial moraine. However, about one eighth of the circumference lies under the foothills of the Jura and here the tunnel must pass through the limestone rock where a boring machine cannot be used. Since the surface of the ground is itself not flat over this huge area, the plane of the machine is not horizontal, but slightly inclined to minimize the distance from the surface to the interaction regions, and hence the cost of the access shafts.

![Figure 2: A LEP Interaction Region](image)

Even with this trick, the interaction regions are typically about 100 metres below the surface. An artist’s impression of a possible interaction region is shown in Fig. 2. Three access shafts will be provided at these regions; one for access to the machine itself; one to allow the large experiments to be installed; one, of smaller diameter, to allow the physicists to intervene at the detector from their control room on the surface.

The planning for LEP sees first beam collisions by mid-1989, and all the four approved experiments, ALEPH, DELPHI, L3 and OPAL, plan to be installed by that date, when the machine should provide electrons and positrons of up to 50 GeV energy. Operation at this energy will use conventional radio-frequency accelerating cavities. This is known as "Phase 1" of LEP which was defined by the CERN Council as follows:
Definition of LEP Phase 1

1. A machine of about 27 Km circumference
2. Enough RF equipment to operate at 50 GeV with useful luminosity
3. Four fully equipped experimental areas out of a possible eight

The initial physics goals of LEP, to be attacked during the first year of operation, are fairly clear. The following areas will certainly receive much attention:

- \( Z^0 \) mass & width; \( M_{Z^0} \) to 0.1-0.2 GeV \( \Rightarrow \) Weinberg angle (\( \pm 0.001 \) in \( \sin^2 \theta_W \))
- Electro-weak asymmetry near the pole \( \Rightarrow \) Weinberg angle (\( \pm 0.005 \) in \( \sin^2 \theta_W \))
- \( e^+ + e^- \Rightarrow e^+ + e^- \) (Bhabha Scattering)
- Higgs Search; A "hot" topic of LEP physics! The most promising reaction is:

\[
e^+ + e^- \Rightarrow Z^0 \Rightarrow H^0 + \ell^+ + \ell^-
\]

or at energies above \( M_{H^0} + M_{Z^0} \):

\[
e^+ + e^- \Rightarrow H^0 + Z^0, \quad Z^0 \Rightarrow \ell^+ + \ell^-
\]

where \( \ell = e \) or \( \mu \).

Table 1: Maximum Energies with Superconducting RF

<table>
<thead>
<tr>
<th>Maximum Accelerating Gradient (MV/m)</th>
<th>2 Exp. Areas with RF</th>
<th>4 Exp. Areas with RF</th>
<th>8 Exp. Areas with RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>70.3</td>
<td>83.6</td>
<td>99.4</td>
</tr>
<tr>
<td>3.0</td>
<td>77.8</td>
<td>92.5</td>
<td>110.0</td>
</tr>
<tr>
<td>4.0</td>
<td>83.6</td>
<td>99.4</td>
<td>118.2</td>
</tr>
<tr>
<td>5.0</td>
<td>88.4</td>
<td>105.2</td>
<td>125.0</td>
</tr>
</tbody>
</table>
LEP is in fact optimised for higher energies than those of Phase 1. This can be readily seen from the curve of Fig. 3, which shows the variation of luminosity with the beam energy. The highest luminosity occurs at more than 80 GeV per beam. The values of the luminosity shown on the ordinate should not be taken too literally since this curve is only an example to show the energy dependence. The particular lattice solution used here is not the one to be used at the start-up of LEP, and the values of luminosity will be different than indicated in this figure.

The possible increase in LEP energy is linked with the use of superconducting materials for the RF cavities. The eventual energy of "Phase 2" of LEP depends critically on the maximum accelerating gradient which can be achieved. This is illustrated in Table 1, where the maximum energy per beam is shown for various accelerating gradients and total cavity lengths. Research and development of suitable
super-conducting cavities is progressing very well, and it is believed that further energy increases will occur adiabatically by the gradual addition of such cavities in the available straight sections and the eventual replacement of the original copper cavities by super-conducting ones. The final operating energy thus attainable should be above the W-pair threshold.

The four LEP experiments are under construction by large collaborations of physicists and engineers, representing many institutes and laboratories from around the world. We will now look at the details of these four approved detectors to see how they prepare for this exciting physics era.

2. THE LEP EXPERIMENTS

2.1 OPAL

![OPAL Detector Diagram]

Figure 4: Overall view of the OPAL detector

This detector, whose name represents Omni Purpose Apparatus for Lep, is probably the most conventional of the four LEP detectors. Many of its design features are based on proven techniques used in the JADE detector at PETRA. An overall view of the OPAL detector is shown in Fig. 4.

The OPAL detector measures charged tracks with a vertex detector and a central tracking chamber, both designed to operate at 2-4 bar pressure. The electromagnetic calorimeter is outside the coil and is followed by a hadron calorimeter and muon chambers.

The vertex detector surrounds the beam pipe and is of active length 1 metre and covers the radial space from 85 mm to 235 mm. This small drift chamber should provide high precision $(r,\phi)$ measure-
ments \( \approx 50 \, \mu m \) and a \( z \) measurement better than 1 mm. A \( z \)-coordinate readout from the \((r,\phi)\) cells based on pulse propagation time difference will provide \( z \) information for triggering with precision \( \approx 2\% \) of the wire length. The outer 35 mm will contain a device to provide precise \( z \) information.

The central track detector of OPAL is a jet chamber with wires 4 metres long. Tracking accuracies between 110 \( \mu m \) and 150 \( \mu m \) have been obtained for drift distances up to 16 cm and the relative \( z \)-resolution is \( \approx 1\% \). By sampling the ionisation of a particle up to 160 times, a relative particle identification by \( dE/dx \) of 3-4\% is obtained giving \( \pi/\rho \) separation.

\[ \text{Figure 5: The OPAL electromagnetic calorimeter} \]

The track detection of OPAL is completed by separate \( Z \)-chambers located outside the jet chamber, in the form of 24 azimuthal chambers each 4.5 metres long in the \( z \)-direction and containing eight bi-directional drift cells each 56 cm long. A prototype chamber at atmospheric pressure has been tested in magnetic fields of 4 and 10 kilogauss.

A solenoidal magnetic field of 4 kilogauss is provided by a conventional (warm) coil of 2.25 m radius. The Collaboration plan to replace this with a superconducting coil giving up to 10 kilogauss field at a later stage.

Immediately outside the coil, time-of-flight counters will be installed. These are immediately followed by the electromagnetic calorimeter which is composed of lead glass blocks in a pointing geometry as shown in Fig. 5. Each block, of thickness 23.9 \( X_0 \), will be viewed by a Hamamatsu R2238 photomultiplier tube. In order to maintain spatial resolution for electromagnetic showers behind the coil, the calorimeter is preceded by a "presampler" comprising two layers of Iarocci tubes (each offset by half a cell) equipped with cathode strip readout.
Hadron calorimetry is provided by interleaving the 10 cm thick iron plates of the solenoid return yoke with carbon coated plastic tubes operating in the limited streamer mode. Muon identification will be obtained by four layers of drift chambers outside the iron return yoke.

The end-caps are similarly equipped with electromagnetic and hadron calorimeters as well as forward muon chambers. The read out of the lead glass blocks of the forward electromagnetic calorimeter will be by vacuum phototriodes which have been shown to tolerate the magnetic field when its axis is < ±30° with respect to the normal to the photocathode.

2.2 ALEPH

![Figure 6: Overall View of the ALEPH Detector](image)

The ALEPH detector is technically more ambitious than OPAL, and is based on a large superconducting solenoid (5.3 m in diameter and 6.4 m long) to provide a magnetic field of 15 kgauss. The central detector is a large Time Projection Chamber (TPC) 3.6 m in diameter and 4.8 m long, and this should lead to optimum momentum measurements on charged tracks.

The overall layout is shown in Fig. 6. As with OPAL, the beam pipe is surrounded by an inner track chamber whose main function is to provide trigger information on charged tracks. Precision of 100 μm is the goal in the (r,φ) projection. This detector will not be described in detail.

The TPC of ALEPH is a key component of the detector, and although based on the PEP4 TPC, contains some novel features. The end plates are divided into 18 sectors of three different types, and they are arranged to give a radial “zig-zag” boundary between sectors, thus ensuring that straight tracks never fall completely on a radial boundary. Furthermore the pad structure is in the form of 21 con-
centric circles, each pad having a radial length of 30 mm and a width of 6.5 mm. Each end-plate contains 20,500 pads and 3240 wires. The use of circular pad rows eliminates, for stiff tracks, a term in the resolution function caused by fluctuations in the size of the avalanche on each wire and proportional to the angle between the track and the pad axis. Figure 7 shows a sketch with the dimensions of the ALEPH TPC.

Extensive tests have been carried out on a prototype (called TPC90) using laser beams and cosmic rays in a magnetic field up to 12 kgauss. Tests of various schemes for "gating" the TPC have been investigated, as well as tests of production techniques for the field cage etc.

Immediately outside the TPC, the electromagnetic calorimeter is located. ALEPH have chosen to use a lead/wire-chamber sandwich technique for their electromagnetic calorimeter. The chambers are made from aluminium extrusions with readout by cathode pads. Pads from consecutive planes are connected to form towers pointing to the intersection region, summed in three depth layers corresponding to the first 4Xo (10 layers), the central 9Xo (23 layers), and the last 9Xo (12 layers). Lead sampling of 2 mm is used for the first and central layers, and of 4 mm for the last layer. The same technique is used for the end-caps.

The lateral size of each tower as seen along its axis is typically 3×3 cm². The segmentation in azimuth angle is ≈1°, and is similar in polar angle near 90°.

Outside the superconducting coil, the return yoke is instrumented as a hadron calorimeter and muon detector. The iron is in the form of 5 cm plates and planes of streamer tubes are interleaved between subsequent plates. A total of 23 plates (of which the last is 10 cm thick) make up the total iron thickness of 120 cm. Each tube layer is equipped with pad readouts on one side for integrated energy flux measurement, and with strips parallel to each tube on the other side, which yield digital information as the basic tool for muon identification.

The pad readout is organized into projective towers, each tower being longitudinally divided into two parts. Resolution of ≈ 85%/√E is expected with good linearity up to 30 GeV.

External to the magnet, both in the barrel and the end-cap regions, two double layers of streamer tubes are installed to detect muons traversing the full iron and measure their direction.
The L3 detector is a special purpose device whose aims are to measure photons, electrons and muons with a resolution $\Delta p/p \approx 1\%$, to measure hadron jet energies with good resolution, and measure vertices with high precision.

The overall view of the L3 detector is shown in Fig. 8. Charged particles from the interaction are tracked in a Time Expansion Chamber (TEC) out to $r = 50$ cm with high spatial and double track resolution. Electrons and photons will shower in a cylindrical array of Bismuth Germanate Oxide (BGO) of thickness $22 X_0$. Hadrons which start to shower in the BGO will continue into the hadron calorimeter extending out to $r = 217$ cm. Only muons will penetrate into the muon spectrometer where they will be momentum analyzed in a magnetic field of 5 kilogauss by three layers of chambers extending out to $r = 568$ cm. The magnetic field is provided by a warm coil of octagonal shape constructed from welded aluminium plates. The inner radius of the aluminium conductor is 5.93 m and the outer radius is 6.82 m.

The TEC vertex chamber uses a low drift velocity in order to detect the shape of the anode signal and use its centroid to define the drift-time value, rather than the leading edge of the pulse. In addition, double anode wires are used to resolve the left-right ambiguity. The aim is to obtain position resolution $\leq 30$ $\mu$m and double track resolution $\leq 500$ $\mu$m to permit lifetime measurements on short-lived particles and momentum measurements on charged tracks.

The electromagnetic calorimeter of L3 will be constructed from BGO crystals. The number of segments in the barrel region (42°-90°) has been fixed to be 160 in azimuth and 48 in polar angle, whilst the geometry of the end-caps is not yet final. The light from each BGO crystal will be detected by a photodiode. Intensive prototype work is under way, and industrial methods for cutting and polishing the crystals have been determined. A sketch of this calorimeter is shown in Fig. 9.
Hadron energy which is not deposited in the BGO (1 absorption length) will be detected by a fine-grained calorimeter containing 4 absorption lengths of depleted uranium and instrumented with wire chambers. Any hadron energy which leaks beyond the uranium will be detected in the muon filter, which comprises 2 absorption lengths of copper and is instrumented with streamer chambers.

Figure 10: Sketch of L3 Muon Detector
The muon detector of L3 comprises two halves each containing 8 octants fixed on a torque tube. Each octant contains three types of momentum chambers and four "Z" chambers which form the covers of the inner and outer momentum chambers. A sketch of an octant showing the assembly technique is shown in Fig. 10.

2.4 DELPHI

![Diagram of DELPHI detector](image)

**Figure 11: Sketch of the DELPHI Detector**

This detector, whose name represents DEtector with Lepton, Photon, and Hadron Identification, is an ambitious one in which, in addition to the general features found in large solenoid detectors such as OPAL or ALEPH, hadron identification is obtained over a large part of the full solid angle and over a good momentum range by means of special ring-imaging Cherenkov counters.

A sketch of the DELPHI detector is shown in Fig. 11. Immediately surrounding the beam pipe is a vertex detector. This device, based on silicon $\mu$-strips, is under development in the Collaboration. It is planned for implementation after the start-up of LEP and will not be described further here.

Outside the vertex detector is the inner detector which comprises a small jet chamber between 12 and 22 cm radius segmented azimuthally into 24 segments which will provide a track trigger in the $(r,\phi)$ plane. The novel feature of this chamber lies in the arrangement of the drift field such that the drifting electrons have a constant angular velocity towards the detection plane. Tests have shown that even for tracks producing the longest drift times within the 15° sector, the spread in arrival time of the signals is within ± 50 ns, which leads to a very powerful track trigger. Outside of this is a trigger layer comprising 5 layers of axial wires read out by cathode strips to yield z-coordinates. In addition to providing fast trigger information, the inner detector forms the first of a series of track chambers used in DELPHI, providing 24 point measurements, each with ≈100μm precision.
In the barrel region, charged tracks are first measured by the inner detector, then by a TPC covering the annular region from 30 cm radius to 120 cm radius and with active 1/2 length of 130 cm, and finally by an outer detector at about 200 cm radius comprising five staggered layers of 1.8 cm square drift tubes, each 4.8 m long in the z-direction, operating in the limited streamer mode. In the forward region, good momentum measurement capability is maintained by the use of two packs of forward drift chambers, chambers A and B respectively.

The DELPHI TPC is similar in dimensions and construction to the PEP4 TPC. The two end plates will be divided into 6 sectors as in PEP4, but the 16 pad rows will be circular. The contribution to the resolution due to $E \times B$ and track angle effects has been studied for different pad geometries.

The DELPHI TPC will use short pads (8 mm along the radius) rather than long pads, such as chosen by ALEPH, since the simulation shows that the $(r, \phi)$ resolution is only slightly worse for high momentum particles but is substantially better at low momenta.

![Figure 12: The DELPHI TPC Endplate](image)

The mechanical construction of a sector plate is shown in Fig. 12. The readout will use a newly developed 8-bit 15 MHz flash ADC, rather than CCDs.

Charged particles emerging from the TPC are identified by velocity measurement in ring-imaging Cherenkov (RICH) counters. The Barrel RICH occupies the annular region from a radius of 123 cm to a radius of 197 cm, and covers the angular region from 41.5° to 90°. A drawing of the Barrel RICH is shown in Fig. 13.

Particles first traverse a thin (1 cm) liquid radiator cell containing freon (C6F14), and if their velocity is above the threshold, Cherenkov light is emitted in a narrow cone which emerges through the quartz of the radiator cell and enters one or more of the drift-tube cells, also through quartz windows.
Inside each drift-tube, the gas contains sufficient TMAE to absorb the Cherenkov photons by photo-ionization within the first 2-3 cm. Since there is a uniform drift field inside the tubes, the ionization electrons drift along the tube to its end where they are detected by a picket-fence MWPC in which each wire is optically separated from its neighbour, as shown in Fig. 14. The hit anode wire gives the \((r,\phi)\) coordinate and the time of arrival of the signal gives the \(z\)-coordinate of the detected Cherenkov photon. The cathode strip barycentre gives the radial (depth) coordinate at which the ionization occurred.
Higher momentum particles which emerge from the liquid radiator can pass through the drift tube region and into the gas radiator region containing another freon (C5F12) where, with sufficient velocity, they will also radiate Cherenkov photons. Since about 45 cm of radiator gas is traversed, the light must be focussed by parabolic mirrors onto the drift tubes, passing through quartz windows on the outer face, and producing photo-ionization electrons close to that face. They will drift down to the MWPCs in the same way as before. The depth coordinate measured by the cathode strips allows separation between electrons from the two kinds of Cherenkov rings. With the radiator gas at 1.3 atmospheres pressure, ≈11 photoelectrons should be obtained from a relativistic particle, and these are all in one drift-tube due to the focusing of the parabolic mirrors.

A Cherenkov ring image from the liquid radiator will typically fall on three adjacent drift tubes and will produce ≈20 photoelectrons. The actual number detected should reach ≈ 16 provided optimum operating conditions are maintained.

Charged particles emitted at < 35.5° pass through the Forward RICH. It is similar in principle to the Barrel RICH but the drift tube technique is not applicable because of the magnetic field. Hence the photon detector is divided into 12 independent TPC units, each covering 30° in azimuth. Time does not permit a more detailed description of this detector.

Electromagnetic calorimetry in the barrel region of the DELPHI detector is provided by a novel device known as the High-density Projection Chamber (HPC). This is a lead/gas sampling calorimeter in which the ionization electrons are drifted along the sampling slots to proportional chamber detectors at the end of each module. The construction is modular with each module covering 15° in azimuth and divided into eight annular regions in the z-direction.

Figure 15: Assembled Lead Structure of HPC Prototype
The drift-field is established in the HPC by using a lead-wire construction with each wire carrying a different voltage. A photograph of a prototype of an HPC module is shown in Fig. 15.

The attraction of the HPC lies in its spatial and angular resolution at an affordable cost. For example, prototype measurements have demonstrated the angular resolution for reconstruction of the axis of an electromagnetic shower to be ≈40 mrad/\sqrt{E} in the drift direction, in agreement with shower simulations. The energy resolution will be ≈18%/\sqrt{E}.

The forward electromagnetic calorimeter of DELPHI will be made from lead glass blocks read out by vacuum photodiodes. The detail of construction will not be given here. The magnetic field of DELPHI will be 12 kilogauss, provided by a superconducting solenoid of radius 2.75 m.

The iron return yoke, which is in the form of 5 cm laminations, is used to provide hadronic calorimetry, by the insertion of streamer tube detectors, which are read out in a projective tower geometry by cathode pads grouped together to give four samplings in depth.

Two planes of muon chambers complete the DELPHI detector, the first plane being inside the return yoke, the second outside. The chambers are flat drift chambers ≈4 m long and having a maximum 10 cm drift distance to a central anode wire. The precision is ≈1mm in the drift direction and the z-coordinate will be measured to ≈10 mm by delay-line readout.

3. DATA ACQUISITION

![Diagram](image)

*Figure 16: Data Acquisition in High Energy Physics Experiments*
Data acquisition comprises the transfer of information from the detectors to the storage medium, which has traditionally been magnetic tape, often passing through an Instrumentation Bus, as shown in Fig. 16, usually either FASTBUS, CAMAC or VME. The choice of this bus depends on many factors but the amount of data to be transferred plays a major role. A detailed discussion of data acquisition systems for modern collider experiments has been published [1] by Gavillet.

3.1 Quantity of Data

<table>
<thead>
<tr>
<th>Detector</th>
<th># Channels</th>
<th>Type</th>
<th># FB Modules</th>
<th># FB Crates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Analog+Digital</td>
<td>Mech.+Stand.</td>
</tr>
<tr>
<td>I.D.</td>
<td>1800-600</td>
<td>FADC+LTD</td>
<td>72 + 24</td>
<td>4 + 4</td>
</tr>
<tr>
<td>B TPC</td>
<td>22000</td>
<td>FADC</td>
<td>258 + 258</td>
<td>36 + 36</td>
</tr>
<tr>
<td>A B-RICH</td>
<td>13000</td>
<td>LTD</td>
<td>264 + 264</td>
<td>24 + 24</td>
</tr>
<tr>
<td>R O.D.</td>
<td>7000</td>
<td>TD</td>
<td>140</td>
<td>7</td>
</tr>
<tr>
<td>R HPC</td>
<td>19000</td>
<td>FADC</td>
<td>576 + 576</td>
<td>24 + 24</td>
</tr>
<tr>
<td>E TOF</td>
<td>400</td>
<td>TSU+ADC</td>
<td>48 + 4</td>
<td>3</td>
</tr>
<tr>
<td>L HCAL</td>
<td>24000</td>
<td>non-FB</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>B-MU</td>
<td>4500</td>
<td>LTD</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>E CH-A</td>
<td>2000</td>
<td>LTD+MUX</td>
<td>12 + 36</td>
<td>6</td>
</tr>
<tr>
<td>N CH-B</td>
<td>4800</td>
<td>LTD+MUX</td>
<td>104 + 48</td>
<td>12</td>
</tr>
<tr>
<td>D F-RICH</td>
<td>*** F-RICH ELECTRONICS IS STAGED ITEM ***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C F-ENC</td>
<td>10000</td>
<td>non-FB</td>
<td>20</td>
<td>10 + 2</td>
</tr>
<tr>
<td>A F-MU</td>
<td>2400</td>
<td>LTD</td>
<td>50 + 64</td>
<td>3 + 4</td>
</tr>
<tr>
<td>P SAT</td>
<td>4000</td>
<td>ADC</td>
<td>125</td>
<td>4 + 8</td>
</tr>
<tr>
<td>S DAS/Trigger</td>
<td></td>
<td>Divers</td>
<td>180</td>
<td>18</td>
</tr>
<tr>
<td>TOTALS</td>
<td></td>
<td></td>
<td>1384 + 1777</td>
<td>105 + 154</td>
</tr>
</tbody>
</table>

Each LEP Experiment will yield large quantities of data because of the numerous components of each of these experiments. As an example, the number of detector channels in DELPHI is shown in Table 2. The whole detector comprises > 120,000 electronic channels contained in > 3,000 modules in some 260 FASTBUS crates.

In order to manage the data recording problem which such large numbers of channels pose, there are two methods to minimize the amount of data which must be recorded. These are:

a) Zero suppression

b) Selective triggering
Zero suppression is simply a mechanism by which one may detect electronically whether a given channel contains useful data or only zeros. If the latter is true, the channel is simply ignored.

The action of zero suppression takes place in the front-end units of the data acquisition system whereas the process of triggering is often split into several levels and can involve both dedicated special hardware as well as programmable devices from microprocessors to full-fledged computers. The "tree-like" structure of data acquisition systems is shown schematically in Fig. 17. Data from many different sub-detectors is combined in the flow from the front-end units to the ultimate mass storage device, passing through trigger/filter stages en route.

3.2 Triggering

Selective triggering is the way that one decides which "events" are to be recorded on the output medium. All LEP experiments would like to record all those events in which an \( e^+e^- \) collision has occurred. On the other hand, the LEP experiments would all like to minimize the number of "background" events which are recorded.
Figure 18: DELPHI Trigger, Filter and Data Acquisition Diagram

The LEP beams are bunched so there is a natural time structure during which $e^+e^-$ collisions can occur. It is a $\delta$-function once every 23 $\mu$s. The time of occurrence of this $\delta$-function is known as the "beam crossing". The trigger of DELPHI will be described but those of the other LEP experiments are similar in concept. The DELPHI system (Fig. 18) comprises no less than four levels of triggering and these will be described in some detail.
3.2.1 First Level Trigger

This is essentially a pre-trigger whose purpose is to decide in 3 μs whether to keep open the gate of the TPC. Its structure is shown schematically in Fig. 19. Note that this figure indicates the early design goal of 2 μs which has now been increased to 3 μs. The basic pretrigger demands a beam crossing signal and a minimum of track and/or energy deposit information. The aim is to reduce the potential number of events from the beam crossing rate (1 every 23 μs or 45KHz), to about 1 KHz.

3.2.2 Second Level Trigger

This is a full trigger level, shown schematically in Fig. 20, in which one tries to reduce the background by requiring:

a) directionality — tracks from vertex

b) threshold on neutral energy deposit

c) cut on transverse momentum

258
The decisions are still at the level of the individual sub-detector (i.e. few links between detectors). The decision must be taken in \( \approx 35 \, \mu s \) so that only one beam crossing is "lost". However if the 2nd level result is yes, the digitized pulses from the analog detectors are stored, and the front-end electronics is "freed" for the next event. This takes \( \approx 500 \, \mu s \). The reduction in rate for the 2nd level is from 1 KHz to about 20 Hz. The digitized data are stored in a 4-deep event buffer and further transfer is not in synchronism with the beam crossing.

3.2.3 Third Level Trigger

At this level, shown diagrammatically in Fig. 21, we are asynchronous, and the processing of the third-level trigger can be carried out during the transfer of the bulk of the data from the individual sub-detectors to a multi-event buffer where all the data can be accessed. At this level, the trigger data is checked with the optimum resolution and good calibration. Furthermore, correlations between sub-detectors can now be used to refine the selectivity. However, the data used is still that based on those tracks or calorimeter zones which led to the original 1st and 2nd level decisions. The output rate from the third-level is expected to be less than 5 Hz.
3.2.4 Fourth Level Trigger

In DELPHI this is also known as the filter or tagging stage. It is the final selection of events before they are written to the output medium. Its purpose is to replace the "filter" stage of off-line analysis often used in experiments at PEP and PETRA. In order to achieve the desired CPU, DELPHI will use five 3081E emulators in parallel. A diagram showing a possible implementation of this concept is shown in Fig. 22. The five emulators will contain filtering code developed on a full IBM mainframe, which will access the full event data. On average, each emulator will spend up to 1 second analysing the event it is processing. The information on accepted events (at 1-2 Hz) will be stored for further off-line use. Other experiments use other techniques with similar goals. ALEPH will use special processors based on µVAX chips plugged into the VAXBI bus of their DAQ computer.

3.3 Read-out Architecture

The read-out of the data in DELPHI follows closely the sub-detector structure present in the experiment. The read-out is divided into partitions corresponding to the sub-detectors, and has a buffered structure as shown schematically in Fig. 23. Each partition is composed of front-end crates and
equipment computer crates. The latter are each linked to an equipment computer (μVAX) which deals with the monitoring of the sub-detectors. The data acquisition electronics of the DELPHI experiment is in the FASTBUS standard. Master modules using MC68000 microprocessors will manage the data flow. After an acceptable 2nd level trigger, the electronics data is digitized and, after zero suppression, is stored in front-end buffers (4 deep) in each partition (FEB). The microprocessors are then used to transfer the data asynchronously into a multi-event buffer (MEB) also 4 events deep.

During the time required to transfer the full event data into the multi-event buffer, ≈30msec, the third level trigger processing can take place. If this results in a negative decision, the data transfer is stopped and the pointer in the multi-event buffer is reset, allowing the data from the rejected event to be overwritten by the next event. In the next stage, data from a full event is passed into one of the 3081E emulators and can be processed as described above. Events which are retained pass into the downstream event buffer (DEB) before being read into the Data Acquisition Computer for final formatting and recording.
4. SOFTWARE DESIGN

The way in which software is prepared for large experiments has undergone a major evolution in recent years. The LEP experiments are a good example of this evolutionary change. The ALEPH Collaboration were the first to adopt the use of Structured Analysis and Structured Design (SASD) techniques [2] [3] [4] for their software. Both DELPHI and OPAL followed and used these techniques in parts of their software.

The DELPHI on-line software was designed using SASD techniques where applicable. This was true in particular [5] for the data acquisition in FASTBUS. Thus some of the ensuing figures will use the terminology and style of SASD.

The basic concept in the DELPHI data read-out is of a transfer-processor as shown in Fig. 24. This is an operator which receives data, performs some operation on it and then passes it on to the next stage. The various transfer-processors are shown as rectangular boxes in the layout of the central readout shown in Fig. 25.
Figure 24: Transfer Processor Concept

Figure 25: Layout of the Central Readout System
Within the DELPHI Fastbus Readout, each partition has its own Local Event Supervisor (LES) which receives data from the front-end modules and performs operations on it, such as deciding whether to "spy" on that event. Each LES can control the partition if that sub-detector is in "stand-alone" mode. In full data taking, the LES are under the control of the main Event Supervisor (ES).

![Diagram](image)

**Figure 26: Event Supervisor Software: Context Diagram**

As an example of the use of SASD, the software design of the ES of DELPHI [6] will be briefly described. What follows will not be rigorous and should be regarded as an illustration of the way that SASD techniques have found use in the design of High-Energy Physics software.

The so-called "Context Diagram" of the problem is given in Figure 26. The solid lines represent the flow of data in the direction indicated by the arrows, whilst the broken lines indicate control flows. The "bubble" represents an operation on the data; in the case of the context diagram this is the whole function to be described in more detail subsequently. The rectangular boxes here represent various transfer processors from which data is obtained by the "Supervise DELPHI Readout" process. This process can be broken down into three main parts:

1. **CONTROL READOUT**
2. **ROUTE ERRORS**
3. **MONITOR READOUT BEHAVIOUR**

In the terminology of SASD, this breakdown is described by a Data Flow Diagram or DFD as shown in Fig. 27. Each of the "bubbles" of the DFD represents an operation on the data flowing into it. Again, each bubble can be further decomposed as shown for "CONTROL READOUT" in Fig. 28, where the bubble 1 has become bubbles 1.1, 1.2 & 1.3. The further decomposition of bubble 1.1 is shown in Fig. 29 in which the bubbles have become sufficiently elementary in nature that further decomposition is no longer necessary.
Figure 27: Event Supervisor Software: Top Level DFD (DFD_0)

Figure 28: ES_CONTROL: Main Functions (DFD_1)

1. Handles turnout: No LES responds
2. Handles T3P turnout: overall turnout if neither T3-RES nor RO-DONE-V-LES received
The power of SASD lies in the way that Data Flow Diagrams (DFDs) such as those shown in Figs 26-29 can provide a powerful way for system designers to discuss the logic of the software with their colleagues before any code is written and thus eliminate many possible logical errors at this early design stage.

The next stage is to pass to the preparation of "Structure Charts" based on the established DFDs. These are established by following formal rules which will not be discussed here, and for which some automatic tools are becoming available on the market. Two examples derived from the DFD shown in Fig. 29 are shown in Figs 30 & 31. The rectangular boxes of the Structure Charts can now be clearly identified with the conventional structure of sub-routines with which you are all familiar. The horizontal lines show buffers which are accessed by several routines. The arrows show data passed from/to the called routines and the dotted boxes are expanded in further diagrams. That corresponding to two such boxes in Figs 30-31 is shown in Fig. 32.

Once the Structure Charts have been checked by the design team, and amended where errors have been detected, the coding can begin. Note that up to this stage the whole process is language indepen-
Figure 30: ES_CONTROL Structure Chart: Handle "Good_T2" from TS

Figure 31: ES_CONTROL Structure Chart: Handle "RO/ABORT_DONE"

dent. It should also be self-evident that the DFDs and Structure Charts form an excellent basis for the documentation of the software and greatly simplify the maintenance task.
A further important tool of SASD especially in real-time applications is the "State Transition Diagram" (see Ref.3). This will not be discussed here for lack of time, but those wishing to explore SASD further should be aware of this powerful concept.

5. DATA ANALYSIS

The phase known as data analysis goes from the raw data, stored on some medium such as magnetic tape, to the appearance of a publication of physics results. All the LEP experiments will produce large amounts of data on the Z⁰ peak. The following table (Table 3) is an estimate for one experiment (ALEPH).

<table>
<thead>
<tr>
<th>Year</th>
<th>Hours</th>
<th>Lumin</th>
<th>Z⁰ events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>2000</td>
<td>1.10^{30}</td>
<td>0.2.10^{6}</td>
</tr>
<tr>
<td>1990</td>
<td>3000</td>
<td>1.10^{31}</td>
<td>2.7.10^{6}</td>
</tr>
<tr>
<td>1991</td>
<td>3000</td>
<td>2.10^{31}</td>
<td>6.5.10^{6}</td>
</tr>
</tbody>
</table>
All the experiments want $10^7$ events on $Z^0$ and each event will be $\approx 100$-200 KB in size! Data storage requirements are thus very important!

5.1 Data Storage

What technology should be used? The following are candidates for mass-storage technology:

- Magnetic Disk
- Magnetic Tape (or cassette)
- Optical Disk

5.1.1 Magnetic Disks

These are traditionally used for very rapid access and heretofore have been of limited capacity and rather high cost per unit of storage space (Megabyte or Gigabyte, shortened to MB or GB). However, the technology is under rapid evolution and one can now see disks emerging with capacity up to 7.5 GB. These can be mounted in sets which can reach 100-200 GB.

Along with the growth in disk capacity, one sees a fall in the cost per MB. The price now is about 20$/MB$ but this should fall to 4$/MB$ by 1990 if the current trends continue.

5.1.2 Magnetic Tapes

Magnetic tapes are serial devices and are inherently slower than magnetic disks. To read a particular record, one must spool through the tape to find the desired location and then read it. Cassette Tapes (e.g. IBM 3480) look to be very attractive as the convenient packaging for the future. At the moment, only IBM offer a viable product but other manufacturers are close behind. Currently their capacity is limited to 200 MB/tape only, but an increase to 400 MB/tape is expected in 2-4 years (double density). Their price is now 24$/cassette$ and decreasing rapidly such that they are favoured with respect to reel-to-reel tapes on cost/MB.

Cassette Tape silos (with up to 6000 cassettes yielding 1200 GB total) are now under test by STC. Some laboratories (SLAC, DESY, CERN?) have placed orders for such units.

5.1.3 Optical Disks

There is very great potential here, particularly for raw data recording (Write Once, Read Many times - or WORM technology). The technology is not yet mature but should yield 1-2 GB/side with direct access at the file level. Thus it is not necessary to spool through the whole device to read a record, but only from the beginning-of-file marker. Cost level (per MB) needs to be $\approx$ magnetic tape if it is to become commercially viable.

5.2 Calibration and Alignment

LEP detectors are very complex! Calibration of the response functions of the sensing elements are required frequently and these calibration constants need to be made available to the off-line analysis.

Accurate reconstruction of an event requires knowledge of relative position of all the sub-detectors. Databases are the obvious technique for storing the alignment and calibration data. The data for these files must be produced either in special runs (using e.g. laser beams for alignment) or by using special triggers (such as cosmic-ray events). The actual calibration and alignment is done in an event pre-processing phase of the analysis. This phase can also include a filtering/tagging option, although this is partly done on-line.
5.3 Event Reconstruction

The streams of filtered and calibrated events are passed through one or more CPU intensive programs to determine the full physics parameters of the events such as:

- momentum and direction of all the produced particles
- types of particles (e, π, μ etc..)

The output of this phase of the analysis is called a Data Summary Tape or DST.

The LEP experiments will each require about 20-30 sec of IBM 168 CPU units for each Z^0 event passed through this phase of the analysis, and need ≈ 5MB of memory. It is hoped that such CPU intensive tasks can benefit from the power of vector processors, but this is not yet sure.

5.4 Physics Analysis

This is an area difficult to plan. It should benefit greatly from the improved interactive facilities now usually available to the physicist. This is where he must use his training and intelligence to extract the physics from the DST. Typical tasks include the histogramming of parameters (see presentation of R. Brun on PAW). From this and other techniques, a selection of interesting events must be made. Once this is achieved, the physicist must then create the mini- and micro-DSTs containing the physical parameters of these interesting events. He will then wish to compare these events with what is called "simulated data" i.e. data created by the computer based on assumed physical laws, thus testing whether these laws are indeed correct. Finally, the physicist will also try fitting models to the data to understand better his results.

The total computing load of the physics analysis is similar to that used in the event reconstruction. However, it is much easier to carry out physics analysis in the many European Universities and Laboratories than it is for event reconstruction. Thus a wider base of computing power is available.

5.5 Event Scanning

This is an important complement to the traditional batch approach for off-line analysis. The technique was used very effectively by UA1 at the SPS collider in their successful search for W and Z events. This approach is where the power of the physicist is used directly to spot new phenomena by visual inspection of event displays, usually on 3D graphics terminals.

Another very important application is to check the validity of the full analysis. The physicist can check that the event reconstruction is optimal by changing some parameters, such as alignment constants or calibration constants, interactively at his workstation or graphics terminal.

5.6 Overall Computing Needs for Analysis

From the estimates which we now make of the rate at which data will be taken, the rejection of background possible on-line, the computer power required for calibration and alignment, event reconstruction, event simulation, and physics analysis including interactive event analysis, it is generally believed that each LEP experiment will require ≈ 12 IBM 168 units of CPU power at CERN and an equivalent amount or more in its collaborating institutes. The physicists in the LEP experiments are doing all in their power (see the presentation of Richard Mount at this school) to ensure that this amount of compute power will be available by 1990 when we all expect the large amounts of LEP data to become available.
6. ACKNOWLEDGEMENTS

A presentation of this kind would be impossible without the cooperation of all the four LEP experiments from whom vital information was obtained. The author would like to express his thanks to the spokesmen for their kind help and provision of the latest photographs concerning the LEP detectors. The sections on data acquisition and computing were based strongly on the DELPHI experiment, of which the author is a participant, and he wishes to acknowledge the work of many people working in DELPHI, too numerous to be listed here, who have contributed to these concepts over the past five years.

* * *

References