Chapter 7

The Large Electron Positron Collider (LEP): Probing the Standard Model

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7.1 Introduction

LEP: Its origins

B. Richter, co-discoverer of the J/ψ particle and Physics Nobel Laureate of 1976, was visiting CERN in 1974, where he launched the idea of a very Large Electron Positron (LEP) Collider [1]. It needed to be large to provide enough energy for the discovery of the postulated Z and W bosons [2]. Their masses were estimated to be close to a hundred times that of the proton, based on experimental constraints and growing confidence in the Standard Model (SM). The physics community was rapidly convinced that this should be the next big European facility. Building on the successes of circular colliders such as SPEAR, with PETRA and PEP on the way, and anticipating a circular tunnel that could eventually host a very high energy proton–proton collider, the choice of a circular machine appeared logical.

In 1978 a first important milestone was reached in a workshop held in the alpine village of Les Houches [3]. The physics programme was evaluated, machine parameters studied and conceptual experimental installations developed. The Director-General at the time, J. Adams, presented a possible planning, which in the event turned out to be quite close to the mark. The mood of the community was upbeat: “LEP’s do it” was the motto adopted by the workshop participants. Under the aegis of ECFA a working group was set up where accelerator and experiment communities worked together, creating strong motivation for the new project [4], and other conferences on experimentation were organized in quick succession [5].

The second milestone was the proposal in 1980 to use the existing synchrotrons, the PS and the SPS, as injector for LEP, once again demonstrating the wisdom of the strategy of keeping all accelerators together on one site [6]. This preempted all discussions on the possible site of LEP elsewhere in Europe and

avoided the highly political debate on siting which had overshadowed and delayed the SPS project.

In 1982 the LEP project was authorized by all Member States. Meanwhile the LEP team had continued to work on the optimization of the design and on the exact location of the ring. The LEP Management Board, with E. Picasso as Chairman, the LEP Experiments Committee and the LEP Machine Advisory Committee were put in place. In 1983 the civil engineering started. The same year the Z^0 was discovered with a mass close to $92 \text{ GeV}/c^2$, as predicted by the SM, well within LEP's reach. In February 1988 the LEP tunnel excavation was completed. Only 17 months later the first Z^0 s were enthusiastically registered in the four experiments. The competition of the Stanford Linear Collider, SLC, in Stanford, USA, with much less luminosity but with longitudinal polarization of the beam [Box 7.1], further increased the motivation. After 7 years devoted to Z^0 physics (LEP1), the beam energy E_b was progressively increased (LEP2).

Pre-LEP physics landscape

In 1986 a seminal Workshop at CERN focused on the LEP physics programme [7]. The foundations of precision tests of the electroweak (EW) theory [Box 6.4] were laid and the experimental methods defined in detail.

For the strong interactions, experimental evidence pointed increasingly to the validity of QCD [Box 4.2]. Asymptotic freedom, the vanishing of the strong coupling at small distance — the most unexpected property of the strong force — had been theoretically predicted in 1973. Experimental evidence for the gluon, mediator of this force, was found at PETRA at DESY in 1979. But the predicted energy-dependence of strong coupling still had to be demonstrated and jet studies (started at the ISR, $p\text{--}\bar{p}$ collider, PETRA and TRISTAN) had to be pursued.

Of the three generations of quarks and leptons, only the top quark remained elusive. There was little doubt as to its existence, and its mass was suspected to be around 40 GeV. If so, LEP would be ideal to perform new subtle “onium” spectroscopy of top–antitop bound states, just as charm and beauty had been revealed through gamma transitions measured with appropriate high resolution calorimetry [Highlight 7.9]. But “top” turned out to be much heavier than expected and this physics did not appear: the possibility of more than three generations was still open. The physics of the tau lepton and heavy flavours became an obvious goal.

Supersymmetry (SUSY) had been postulated in the early seventies, with decisive contributions of J. Wess and B. Zumino, then visitors at CERN, but its phenomenology was only starting to be explored. The fact that it required a light SM-like BEH boson was recognized, but an upper limit on its mass ($< 130 \text{ GeV}$) had to wait for more theoretical work and a precise measurement of the top mass.

The LEP machine

The Large Electron–Positron storage ring (LEP) collider was located beneath the border between Switzerland and France, near Geneva. It was to be by far the largest accelerator in the world, with the main ring tunnel having a circumference of the order of 30 km. Although studies and plans for LEP machines of various diameters started as early as 1976 [8], it was not until October 1981 that the project was approved [9]. The tunnel would pass under villages, so the environmental impact had to be evaluated and presented to the municipalities [10].

The maximum beam energy for which the major systems of the 26.7 km circumference machine were to be designed was 125 GeV [11].

While the tunnelling under the plain went well, the 3 km section passing through the Jura limestone was difficult due to water infiltration [12–14]. By dint of a crash programme half of the resulting delay of about a year would be made up during the installation of the machine components. The first beams circulated in July 1989, with physics runs starting a month later [15].

LEP was designed to bring very high energy electrons and positrons into collision [14–16]. Initially, the beams were accelerated to provide a centre-of-mass energy at the collision point of 91 GeV, the rest mass of the Z^0 boson, thereby opening a new world of investigation into the neutral current interactions of the electroweak force. This first phase of LEP, called LEP 1, was a huge success, with over 900,000 Z^0 bosons being produced in the first year. Data continued to be accumulated at the same energy until 1995. Then the machine was upgraded to become LEP 2 [17]. Collision energy was gradually increased by adding accelerating cavities as they became available, which allowed the experiments to search for new particles as well as to study in depth $W^\pm$ and Z pair production. The maximum centre-of-mass achieved was 209 GeV, with the straight sections at the even points filled with cavities, when in 2001 the machine was closed due to pressure for building the next accelerator, the LHC.

Before injection into the main ring the particles had to be accelerated in a number of other, smaller accelerators most of which had been designed and operated previously for other projects. Indeed, it was the existence of these injectors that helped to convince the community that LEP should be built at CERN. Figure 7.1 shows the layout of the complete accelerator complex. The electrons were produced by thermionic emission and accelerated along a linear electron accelerator, the LEP Injector Linac (LIL). Some of the electrons were diverted onto a tungsten target to produce the positrons; the electrons, along with the positrons, were then passed into the Electron Positron Accumulator ring (EPA), where they were accumulated and stored. The particles were then sent to the Proton Synchrotron (PS) where they were accelerated in bunches up to a few GeV.

Following this they were transferred to the Super Proton Synchrotron (SPS) where further acceleration took place prior to injection into the LEP ring [18].

Fig. 7.1. Diagram showing the CERN accelerators at the time of LEP and how they were used to produce the high energy beams circulating in the collider.

The 26.7 km LEP tunnel is situated at between 40 and 150 m below the surface. The plane of the ring is inclined by 1.4%. This was to ensure that no shaft be deeper than 150 m, and that the underground caverns and tunnel be located to the largest extent possible in solid molasse (local sandstone). The ring consists of eight arcs and four straight sections. The arcs were equipped with magnetic cells to guide the beams around the ring. Each such cell was composed of a sequence of bending (dipole), focusing (quadrupole) magnets [Box 2.1] and orbit correctors. The total length of a cell was 79.11 m, with each arc containing 31 cells. Families of sextupole, octupole and skew quadrupole magnets were installed to allow the fine tuning of beam parameters. The beams were accelerated in the straight sections on either side of points 2 and 6 for LEP1 and at all even numbered points for LEP2. The four experiments, L3, ALEPH, OPAL and DELPHI were located at points 2, 4, 6 and 8, where the beams were brought into collision.

This exceptionally large accelerator called for an elaborate geodesy: it was even necessary to take into account the non-uniformity of local gravity due to the proximity of the Jura. This required the adoption of the latest techniques in survey: satellite bearings; two-frequency laser metrology; verification of measurements with stars, etc. The tunnel was excavated in two directions and the closing error was less than 2 cm. The slope of the plane of the machine meant that every piece of equipment that was installed required its own survey parameters [Highlight 7.5]. It was also found that the position of the moon had a measurable effect on the diameter of the machine; this had to be taken into account to determine precisely the energy of the beams and thus the Z boson mass [Highlight 7.6].

Synchrotron radiation leads to an energy loss per turn proportional to E^4/R , i.e. increasing with the fourth power of the beam energy E , and gives rise to upper limits for both current and energy. The radius of curvature of the ring R was therefore maximized, respecting other constraints. The main loss of particles is through beam–gas interactions, so good vacuum is essential. Synchrotron radiation also causes heating of the vacuum chambers, and so the chamber walls were made of aluminium, featuring channels through which cooling water flowed, and were covered with lead shielding to protect surrounding equipment. The vacuum was ensured by the incorporation of an innovative system of linearly distributed Non-Evaporable Getter (NEG) pumps [Highlight 7.3].

The designers of the LEP magnet system also had to face up to unusual challenges. The dipole bending magnets had to deliver a maximum field of 0.14 T, about a factor of ten less than usual. To obtain good field quality over the working range it was decided to space the laminations that make up the yokes. In order to have an inexpensive rigid block the space was filled with concrete, pre-stressed with tie-bars, rather than using a structure of girders. An unexpected

problem was posed by the change in the magnetic properties of the iron laminations caused by shrinkage of the mortar [Highlight 7.2]. Another innovative feature of the magnet design was the use of water-cooled aluminium bars, welded end to end, instead of coils wound around the poles, to provide the excitation with reduced overall cost.

On powering the first sector of the machine, unexpected beam parameters (the wavelength and coupling of particle oscillations in the beam) were observed, and traced to magnetization of the nickel flash required to solder the lead shielding to the aluminium vacuum chamber. A method was quickly devised to demagnetize the nickel in-situ, and a crash program was launched to rectify the situation without impacting on the overall schedule.

Due to the size of the machine and the pressure to minimize expenditure on the project, it was important to take into account the cost of cables when optimizing the magnet system. This led to the choice of exceptionally low excitation currents of 2.5 A and 5 A for the corrector magnets. The machine was also equipped with powerful wiggler magnets, to control damping, emittance and polarization.

In order to optimize total system cost it is usual to minimize the aperture in the arcs of a synchrotron, but in the case of LEP, due to the low field, the aperture could be relatively generous without excessive expense. However, this posed a problem for the design of the final focus system as the projection of the arc aperture into the interaction region would have led to very large and expensive quadrupole magnets. This problem was addressed by installing retractable aperture limiting collimators in the arcs, and allowed the use of arc quadrupoles in the insertions. To maximize luminosity [Box 6.1], the final focus magnet system had to be close to the crossing point, so an iron-free superconducting quadrupole was developed that could be cantilevered into the detectors through the poles of the spectrometer magnets [19]. It was also crucially important to control the background in the LEP experiments, so systems of primary, secondary and tertiary collimators were installed on either side of the crossing points.

Copper RF accelerating cavities were used for LEP1. Such cavities are not very efficient, so the RF group developed a novel system of coupled low-loss resonators to store some of the energy during the absence of beam and thereby save power. The 352 MHz copper cavities delivered about 1.5 MV/m and 128 such cavities were used to accelerate beams to 45 GeV. The power consumption problem was also addressed via the development, in collaboration with industry, of efficient klystrons. Despite these efforts, it was clear that to achieve the beam energy for LEP2, superconducting cavities would be essential. The first such cavities were made out of sheet niobium, delivering 5–6 MV/m. It was also decided to explore a new route, namely that of sputtering of niobium onto the surface of a copper

cavity — copper has better thermal conductivity than niobium, leading to improved stability [20]. The technique was perfected and most of the cavities for the upgrade to LEP2 were made in this way. The performance of the cavities gradually improved, and the accelerating gradient could be pushed from 6 MV/m to over 7 MV/m [Highlight 7.4]. The maximum energy achieved, in May 2000, was 104.5 GeV per beam, with 272 niobium-plated cavities, 16 niobium cavities and 56 copper cavities.

The many superconducting cavities of LEP2 called for an abundant and reliable supply of liquid helium, so the CERN cryogenic specialists got together with the two major suppliers of cryogenic equipment to design powerful and efficient He liquefiers. Two plants, each capable of delivering 18 kW of cooling at 4.5 K, were installed at each of two points (2 and 6), one plant feeding the left side and one the right, interconnected so that if a fault occurred in one plant, the other plant could supply both sides and operation be continued (if necessary at a lower energy). The same plants are now used for cooling the LHC magnets [Highlight 8.3].

The project leadership of Emilio Picasso and the enthusiastic support of the Director-General, Herwig Schopper, were vital for the success of LEP (Fig. 7.2).

Fig. 7.2. LEP Project Leader Emilio Picasso and CERN Director-General Herwig Schopper celebrate the completion of the tunnelling of the 27 km ring.

The experimental facilities

For detectors [Box 6.3] the main revolution, which changed the course of particle physics, had occurred at CERN in 1968 with the invention of the Multi-Wire Proportional Chamber (MWPC) by Georges Charpak, for which he was awarded the Nobel Prize in 1992. The MWPC and its derivatives (e.g. drift chambers) had already been developed and used on a large scale at the ISR, SPS and elsewhere [Highlight 4.8]. The Time Projection Chamber, TPC, invented in Berkeley/US had appeared in the late seventies. Liquid argon, scintillating crystal, refined heavy absorber/scintillator calorimeters were already in use (see ISR and SPS). The large collaborations at the SPS and the appearance of the World Wide Web [Highlight 9.7] had paved the way to efficient collaborations on a worldwide scale.

At LEP four state-of-the-art multipurpose experimental facilities had been approved, to be operated simultaneously. Keeping a balance between playing safe and introducing innovative features was a constant concern during their conception and approval phase. All four were ready at the start of LEP and their performances turned out to be similar and, overall, excellent. Several reasons motivated the choice of four simultaneous facilities: to enable a cross-check of experimental results; to stimulate competition between teams; to spread the risk of using novel measurement techniques and to allow the large and interested physics community to participate fully in the research.

While ALEPH [21] and DELPHI [22] incorporated large superconducting solenoids, a bold enterprise at the time, OPAL [23] was equipped with a room temperature solenoid using water cooled aluminium conductor. ALEPH and DELPHI chose as main trackers big TPCs, offering excellent multi-track capability and a good particle identification by dE/dx [Box 5.2].

L3 [24] made use of a large scintillating crystal calorimeter of BGO [Highlight 7.9] and a very large precise muon spectrometer [Highlight 7.10], which required in turn a very large magnet and new methods of alignment and calibration for the spectrometer chambers, paving the way to similar and still larger facilities at the LHC [Highlight 8.12].

The Ring Imaging Cherenkov (RICH) technique was used in DELPHI for particle identification [Highlight 7.8]. Its realization was difficult, but it worked well and stimulated a variety of important developments.

Having realized the importance of charm and beauty identification, all detectors incorporated silicon micro-vertex detectors [Highlight 7.7]. This technique was further developed with the introduction of multi-layer double-sided micro-strip detectors of up to 1 m^2 in area. In the spirit of the UA2 pad detectors [Highlight 6.6], DELPHI introduced pixel detectors, a first at a collider.

Small “luminometers” in the very forward region of the detectors gave the absolute scale for cross section measurements. This started a spectacular competition between theorists computing e^+e^- (Bhabha) scattering and experimentalists measuring it ever more accurately. The race led finally to an accuracy 30 times better than expected (see below).

A very important step was the introduction by ALEPH and DELPHI of their own “PC farms”, using inexpensive Personal Computers interlinked on a large scale, to revolutionize the way computing and data processing was performed.

LEP experimentation also saw the advent of very elaborate quality control procedures for the measurements and analysis and the use of powerful visualization, taking advantage of the “pattern recognition” capability of the human eye, “seeing” the features of events and checking the results of algorithms [Highlight 9.6]. Last but not least, to extract a maximum of information from the LEP measurements the collaborations introduced the practice of combining the results (the ALEPH, DELPHI, L3, OPAL (“ADLO”) collaborations) [25, 26].

The LEP legacy

From its conception and realization up to the completion of its rich physics programme, LEP stands as a very successful project and a landmark in establishing the validity of the Standard Model in all its subtlety. Figure 7.3 shows the scenery of LEP physics in a nutshell, showing the Z resonance and the boson pair cross sections at higher energy, and how the peak luminosity increased over time, to consistently exceed design specifications [16].

Fig. 7.3. LEP physics in a nutshell (see text).

LEP1

The Z^0 mass, one of the three basic entries of the SM, has been measured at LEP1 with 23 ppm accuracy to be 91.1875 ± 0.0021 GeV/ c^2 , by using a resonant depolarization method [Box 7.1]. This value of the mass now appears in the textbooks of particle physics.

The accuracy of measurements of many electroweak quantities improved dramatically during the LEP era. This quest of accuracy was neither an obsession nor art for art's sake, but fundamental to probing the SM at the “loop level”, the mission of LEP, as explained in Box 5.1. The accuracy of the weak angle, a measure of the quality of SM testing, was improved by two orders of magnitude.

Similar progress occurred concerning the number N of neutrino flavours. LEP1 rapidly settled the question, showing that there are three and only three species of light active neutrinos. In fact, N was found to be slightly below 3 — potentially interesting, as it could signal the existence of “sterile” neutrinos, interacting only very weakly with SM particles. Such particles could contribute to Dark Matter and are still actively sought.

Through radiative effects, LEP1, without producing the top particle, showed rapidly that it was quite heavy. It was discovered at the Tevatron in 1996 with a measured mass of 172 ± 6 GeV, while the indirect LEP measurements gave 157^{+16}_{-12} GeV. Nowadays, more precise values are still in marvellous agreement, another triumph of the SM (Fig. 7.4). An accurate top mass is also a key input of modern considerations in cosmology.

Fig. 7.4. Increasing accuracy of the measurement of top mass over time.

Asymmetries

Box 7.1

In e^+e^- collisions, a Z boson can be produced by a left-handed (LH) or right-handed (RH) e^- , the e^+ being then of opposite handedness. The figure shows a LH e^- colliding with a RH e^+ . Given the different couplings of the Z to LH and RH e^- , flipping the handedness of the incoming e^- , as was done at SLAC SLC, allows to measure different Z production rates and the *left-right asymmetry* A_{LR} , and to extract the mixing angle [Box 6.4].

If the incident e^- beam is not polarized, as in LEP, the probabilities for the e^- to be LH or RH are equal. LH e^- , more strongly coupled to the Z, will make more of them (corresponding to A_{LR}). Then a μ^- from Z decay going forward, i.e. in the same direction as the incident e^- (red μ^- arrow in the figure) is LH, while it would be RH if going backward (blue arrow). The former configuration is preferred. Overall, this induces for the μ^- a *forward-backward asymmetry*, A_{FB}^{μ} , at the level of A_{LR} squared, with slightly more μ^- forward. Since opposite to the μ^- there is always a μ^+ , this also implies a *charge asymmetry*.

Using tau lepton pairs instead of muons, one can measure the tau polarization from its decay products, providing another evaluation of the weak mixing angle.

Accurate measurements of such asymmetries for fermion pairs from Z decay were one major test of the SM. Performing this measurement with quarks, appearing as jets, was more involved and the full power of the detectors was needed to identify and measure the charge of the parent quark [Highlights 7.7 and 7.8]. This allowed to measure, e.g. the A_{FB} asymmetry for beauty-antibeauty, A_{FB}^b .

The accuracies reached were such that the effect of loops beyond the lowest order SM predictions could be measured [BOX 5.1]. The mixing angle should be the same at the same energy, irrespective of very different final states and systematic uncertainties. The agreement turned out to be very good, with however a 3σ disagreement between the SLD A_{FB}^b and LEP A_{FB}^b . The accuracy obtained for the weak angle, i.e. one measure of the quality of SM testing, improved by a factor 35 during LEP era, providing sensitivity to virtual particles in loops with up to 13σ significance.

For top, and to a lesser extent, for the BEH boson, good agreement between indirect (LEP) and direct mass measurements (Tevatron, LHC) was a stringent proof of the validity of the SM. Figure 7.4 in the LEP introduction shows the increasing accuracy of indirect (green) and direct (colour) top mass results over time.

LEP could not produce longitudinally polarized beams, but it could polarize the beams transversely. At a precise frequency, a periodic e-m excitation of the beam would *resonantly depolarize* it. This effect was used to determine accurately the *beam energy and thus the Z mass*.

“The search for the top could be compared to that of a bush hunter, his ear to the ground” (G. Altarelli). Once the steps of the elephant “top” were recognized, LEP turned to the much more discrete pace of the tiger — the BEH boson. Assuming the validity of the SM, the boson was felt to be light: ≤ 200 GeV at the end of LEP.

LEP made many outstanding contributions to QCD [Box 4.2], offering in particular a variety of measurements of the strong coupling α_s and a clear proof of its energy dependence. The accurate LEP1 measurements of the couplings of the three forces provided evidence that they might unify at very high energy in a SUSY version of the SM. This suggested a Grand Unification of the forces near 10^{16} GeV, a situation prevailing in our Universe about 10^{-36} s after the Big Bang. It also suggested that SUSY may be more than just an elegant idea.

To resolve anomalies concerning the tau, LEP, in an international venture with other experiments (e.g. BES in China), showed it to be a normal lepton, a recurrence of the first two, albeit much heavier. Its hadronic decays could then be used to test QCD, and as input for estimating μ on $g - 2$ [Highlight 2.4].

With 17 million hadronic Z^0 's recorded, LEP1 was also a tau, charm and beauty factory, and made major contributions to heavy quark physics. The clean topology, the strong boost imparted to the B particle and the fact that all beauty species appear in Z decays were major assets. With the micro-vertex detectors, the performance of their identification exceeded expectations. It contributed to a first hint of CP violation in the world of beauty. On the fascinating particle-antiparticle oscillations much progress occurred. These topics, probably a key to our existence, have been pursued at B factories and now at LHC.

LEP2

LEP2 measured directly the W mass as 80.412 ± 0.042 GeV, while LEP1 (together with SLC) had nailed it indirectly as 80.373 ± 0.033 GeV, another beautiful success of the SM. The measurement of the W pair production offered a spectacular demonstration of the weak bosons self-interaction.

For SUSY, LEP2 set a lower mass limit for some SUSY partners close to the maximum E_b and excluded a LSP (Lightest SUSY Particle, dark matter candidate) lighter than ~ 45 GeV. The SUSY torch is now passed to the LHC.

Concerning the direct search for the BEH boson [27] it was shown that, with a good beauty tag, LEP2 could discover it up to $M_h = 2 E_b - M_Z$, a mass limit that LEP2 indeed reached at each energy. Within the framework of SUSY the existence of a light SM-like BEH boson is predicted. In 1994 the upper limit of its mass was estimated to be 130 GeV in the simplest versions of SUSY. A beam energy of 110 GeV was thus required to verify the existence of such a boson.

Supersymmetry (SUSY)

Box 7.2

Supersymmetry (SUSY) is an attempt to restore the striking asymmetry in the Standard Model [Box 6.4] between constituent fermions and field bosons, by associating with each of the known particles a partner of the opposite category. If SUSY is real, it cannot be a perfect “symmetry” (it must be “broken”), since such partners do not exist having the same mass. SUSY would cure some of the shortcomings and paradoxes of the SM. Mathematically the theory is well founded. In brief, it says that any “step” made in space-time (translation, rotation, boost) can be decomposed into two, from space-time to an entity called *superspace* and back to space-time. Its realization requires the partners quoted above, but says nothing about their mass and the mechanism of breaking the symmetry.

A priori doubling the number of elementary particles does not seem to be a progress. However unbroken SUSY has in fact one parameter less than the SM. Long ago the prediction and discovery of antiparticles, leading to such a doubling, was a decisive step in our understanding of particle physics. But SUSY breaking reintroduces many parameters, which renders this theory difficult to ever falsify.

Searches for SUSY at colliders assume that some partners may be light enough to be accessible. Most assume that the Lightest SUSY Partner (LSP), being unable to decay to a lighter one, is stable, invisible and leads to missing energy-momentum in the final state. Being stable the LSP may also be a cosmic remnant of the early Universe, constituting its *Dark Matter*, and can be searched for as such [1].

Light SUSY would solve the puzzle of the SM, the relatively light mass of the BEH boson, which radiative corrections [Box 5.1] should push to a higher value. Fermions and bosons populating the loops in a nearly symmetric way would much reduce these corrections.

A further virtue of SUSY and its only strict requirement (and possibility of falsification), is to predict (in its minimal version) a light SM-like boson, < 130 GeV. The 125 GeV boson (see LHC) is thus an encouragement but not a proof. Another hint is that in SUSY the coupling constants of the three forces meet exactly at very high energy as shown in the figure.

The search for SUSY partners and LSP has so far been unsuccessful. SUSY partners of the gluon and quarks of the first two families, if they exist, must be heavier than ≈ 1.5 TeV (unless the LSP is heavier than ≈ 0.8 TeV, in which case no limit is set yet). The limits on partners of the 3rd family and of BEH and EW gauge bosons are lower. The search for SUSY partners is a priority at high luminosity and high energy LHC.

[1] H. E. Haber and G. L. Kane, Is Nature Supersymmetric?, *Scientific American*, June 1986.

Fig. 7.5. Increase in energy of the LEP beams.

In 2000, following the remarkable improvement of the RF, LEP2 delivered a useful beam energy of 103 GeV (Fig. 7.5). An indication of a weak signal at $M_h = 115$ GeV was claimed, most insistently by ALEPH. Twelve years later the LHC showed that this signal was spurious and discovered the boson at $125 \text{ GeV}/c^2$.

SUSY or not, LEP2 missed the boson by 10 GeV. Replacing all less performing RF cavities with high-gradient Nb-coated superconducting ones, as proposed in 1996 [28], would have provided the required increment of energy. The production of cavities was stopped in 1996 to free resources for LHC.

The LEP legacy to its off-spring LHC was thus that the SM BEH boson should appear in a mass range between the lower limit of the direct search ($114 \text{ GeV}/c^2$) and the indirect upper limits from electroweak measurements, about $200 \text{ GeV}/c^2$, reducing to $150 \text{ GeV}/c^2$ in 2007 when including the Tevatron results.

In retrospect, it is instructive to compare the expectations of LEP with the results. All measurements exceeded, often by far, the expectations [27]. The achieved error on the Z mass was 2.1 MeV instead of 20 to 50 MeV expected. For the W mass is was 33 MeV instead of 100 MeV. The number of neutrino families was determined with an error of 0.008 compared to 0.3 first anticipated. All asymmetries [Box 7.1] were also measured about 3 times more precisely than foreseen. In addition to the gain from combining the results of the four experiments, this was due to a number of important facts:

- The outstanding performance of the machine, and the excellent collaboration of its team with the experimentalists;
- The relative ease of performing experiments at LEP. Due to the low level of background the interesting events were easy to select and quite clean (Fig. 7.6). Accurate knowledge of E_b permitted to use kinematic constraints;
- The diameter of the vacuum chamber in the experimental intersections could be reduced thanks to clever shielding against synchrotron radiation, so that micro-vertex detectors could be placed close to the collision point to improve b-tagging;
- Redundancy of experimental procedures. Efficiencies could be measured instead of being evaluated from Monte Carlo runs, reducing systematic errors;
- Development of new techniques, some emerging or being improved during LEP lifetime, e.g. the luminometers and micro-vertex detectors;
- Outstanding work of theorists, in close collaboration with the experimentalists, which were key to testing so beautifully the fundamental features of the SM.

Fig. 7.6. A typical event as recorded at LEP.

7.2 Concrete Stuffing for the LEP Magnets

Jean-Pierre Gourber

With LEP, CERN was confronted for the first time with the problem of producing a large number of magnets with a very low bending field. At the maximum design energy of 125 GeV, the field of the main dipole magnets was only 0.135 T, to be compared with the 1.5 T to 1.8 T of classical magnets for protons machines, but it had nevertheless to be very precise and uniform from unit to unit. CERN engineers faced up to the challenge of satisfying this unusual requirement by developing innovative solutions that would also result in substantial savings in cost.

The regular lattice periods in arcs were 79 m long with bending magnets made of six equal C-shaped dipole yokes (cores) between focusing quadrupoles. With the shorter cells at the arc ends, there were in total 3304 cores. These were excited by passing current through long bars of extruded hollow aluminium, insulated with glass-epoxy, and connected in series giving a single powering circuit (see Fig. 7.7). This solution was cheaper than traditional coils and minimized the space required for joints between magnets. The 5.75 m long cores were assembled in pairs at the surface with their common 12 m long excitation bars and lowered into the tunnel via a large elliptical shaft. The excitation bar interconnection was made *in situ* by TIG welding with special care to ensure continuity of the water cooling channel.

The cores were made as usual by stacking low carbon steel laminations. The transverse dimension of the gap was imposed by the dimensions of the vacuum chamber, the required 10^{-4} field homogeneity, and the mechanical stability of the flux return (backleg) during punching. Because of the low field, the laminations

Fig. 7.7. Assembly of dipole magnet yokes at LEP.

could be spaced so that the field level in the flux return would reach the optimum value of 1.5 T at the maximum field, corresponding to 125 GeV. The spaces had to be filled with material cheaper than steel and the manufacturing process had to be economical. Somewhat surprisingly, concrete was proposed as the “stuffing” of choice of the voids between the iron laminations [29, 30]!

The 1.5 mm thick laminations were precision punched from decarburized steel sheet having good magnetic properties. The punching die also pressed suitable indentations which, by alternating the laminations, ensured the required optimum spacing of 4 mm in the stack (Fig. 7.8). The stack of laminations with its two 15 mm thick end plates was then placed in a mould and filled with a low shrinkage mortar. Four longitudinal rods anchored to the end plates were tensioned to provide compressive pre-stress of 0.5 MPa after de-moulding. This ensured that all points remained in compression during manipulation of the cores. The cores behaved like pre-stressed concrete beams; they were only half the weight of full steel cores and being very rigid they could be supported on three feet, making for easy alignment. The magnetic properties of these magnets were nevertheless very close to those of full steel magnets. The local variation of the field in the beam aperture due to the lamination spacing were less than 10^{-7} , and hence negligible.

The punching of the laminations by a single firm and the parallel fabrication of the cores by two civil engineering firms went smoothly and to the schedule of three years. On delivery to CERN, the *magnetic* geometry of the gap of each core was measured using a specially developed carriage. Complementing these survey measurements one core out of ten was equipped with a provisional set of excitation

Fig. 7.8. The construction of the steel concrete magnets.

bars and its field measured. Results met specifications. However, when these measurements were repeated some months later there was a bad surprise: despite the use of a mortar carefully chosen for its low shrinkage, some residual shrinkage was occurring long after the cores were dry. The longitudinal effect of shrinkage had been anticipated in the design of the core, the supports and the excitation bars. But the shrinkage also had an unforeseen effect: it put the laminations into transverse compression. Such stress decreases the magnetic permeability of the steel, affecting the field in the gap [31]. Such a drift was unacceptable for an accurate energy calibration of LEP. The solution was to submit every core, one year after manufacture, to five cycles of a slight opening/closing of the gap, to provoke micro-fissures in the mortar and relieve the compression in the back leg. In addition, each core was equipped with a flux loop embedded in the lower pole. These loops, which were connected in series in the ring, were used to monitor the field in situ so that the influence of temperature variations, and eventual further ageing of the mortar, could be taken into account when determining beam energy.

7.3 Pumping LEP: Sticky Tape for Molecules

Cristoforo Benvenuti

Storage rings need a low residual gas pressure to minimize beam–gas interactions and keep the particles circulating for hours. For an electron storage ring, such as LEP, the problem is aggravated by the synchrotron radiation produced by the beams, which hits the vacuum chamber walls and desorbs a large amount of gas.

The small conductance of the vacuum chamber limits the flow of the gas molecules to the pumps, so reducing their pumping efficiency. At LEP, pumps with one metre spacing would have been needed to circumvent this problem. An elegant alternative solution adopted in similar previous projects consists in replacing the lumped pumps by a linear sputter-ion pump inserted in the dipole bending magnets. In this case pumping is ensured by ionizing the gas by a discharge ignited between two electrodes, and burying the ions in the cathode. The discharge is maintained at low pressure thanks to a high voltage and a high magnetic field applied to the pump. However, the field of the bending magnets at the LEP injection energy was too low to ignite the gas discharge in the pumps. Another solution had to be found. Finally, a getter strip [Box 7.3] inserted all along 23 km of the LEP chambers was adopted, as shown in Fig. 7.9 [32].

Fig. 7.9. Cross-section of the LEP dipole chamber with the getter pump. 1: extruded Al profile, 2: cooling channels, 3: lead shielding for synchrotron radiation, 4: ceramic insulators, 5: pumping slots.

Getters

Box 7.3

Most metals and metal alloys display chemical reactivity with some gases, at least with oxygen (which is responsible for their surface oxidation). Materials able to trap the majority of gases in the form of stable chemical compounds are called getters and are widely used in vacuum technology. However, rare gases and methane do not react with getters, so additional pumping of a different nature must be added.

Getter applications were pioneered by D. G. Fitzgerald (England, 1883) and A. Malugnani (Italy, 1894), both for use in incandescent lamps. Since then getters have been inserted in all vacuum sealed devices to continuously pump the gas produced by components of the device.

A clean getter surface traps gas molecules, but in doing so its reactivity decreases and finally vanishes at saturation. To restore pumping two different strategies may be adopted, which define two different getter families. Evaporable Getters (EG), for which pumping is restored by coating the saturated layer by a fresh getter film, and Non-Evaporable Getters (NEG), for which the surface is cleaned by heating. Heating provides the energy needed to diffuse the trapped gas molecules from the surface into the getter bulk. The two important practical characteristics of NEGs are the surface area, which defines how much gas may be pumped before saturation, and the activation temperature (T_a) required for cleaning the NEG surface.

EGs have been used for Ultra High Vacuum (UHV) applications since the 1950s in the form of Titanium sublimation pumps, but these could not be adapted to provide linear pumping. On the other hand, NEGs were used only at relatively high pressures ($10^{-4}/10^{-6}$ Pa), at which the fast surface saturation imposes continuous NEG heating, not applicable in the case of LEP because it would upset the circulating beams. LEP required pressures lower than that, and the NEG behaviour at low pressures without continuous heating remained to be demonstrated at the time (it has since been confirmed).

Following the approval of the LEP project, vigorous development work was undertaken to explore the possibility of Non-Evaporable Getter (NEG) pumping. At that time only one NEG type was commercially available, in the form of a metal strip coated on both faces with 0.1 mm of getter powder. The getter material was a Zr-Al alloy with a daunting activation temperature of 750°C. The strip width chosen for performance evaluation was 30 mm.

Very quickly after the beginning of the experimental investigation it became clear that pressures as low as 10^{-10} Pa could be obtained by this NEG kept at room temperature. Since in this case gas diffusion does not take place, it was vital to ascertain how much gas could be pumped before reaching saturation.

The answer to this question is given in Fig. 7.10 [33]. The results were reassuring. About 10% of the initial performance was still available after pumping, per metre of NEG strip, 10 Pa litre of H_2 and CO, the most important components of the accelerator residual pressure. In practical units, 10 Pa litre of gas corresponds to about 0.1 cc of gas at atmospheric pressure, a huge amount by UHV standards. This result is a consequence of the active NEG surface area being about 100 times larger than its geometrical area, due to the high NEG porosity.

Although these results were comforting, the wide performance difference for different gases was puzzling and this poor understanding was not acceptable for a multi-billion project. For this reason, a large effort was invested in understanding

Fig. 7.10. Variation of the pumping speed S as a function of the pumped quantity of different gases. The measured sample is the strip (1 m long, 30 mm wide) adopted for the pumping of LEP. The getter is a Zr-Al alloy. (1 Torr = 133 Pascal)

the NEG pumping behaviour for individual gases and gas mixtures [34]. It was found that H_2 diffuses into the NEG bulk even at room temperature, while for heavier gases, which stick to the surface, pumping at room temperature depends on the NEG porosity and on the number of getter atoms needed to trap a gas molecule. The large difference of the pumping curves shown for CO and N_2 in Fig. 7.10 is a consequence of the fact that a CO molecule occupies one NEG atom, while six adjacent, free atoms are required to adsorb a molecule of N_2 , for which the surface saturation is therefore much faster.

The strategy resulting from these studies was to rely on NEG pumping at room temperature and to apply regeneration heating whenever the remaining pumping was too low for the desired performance of the accelerator. Based on this strategy, a few LEP chambers were equipped with different prototypes of NEG pumps and finally the model shown in Fig. 7.9 was adopted. In this pump the NEG strip is electrically isolated from the chamber with ceramic pins inserted into a metal frame. At the two ends of each chamber the NEG strip is connected to electric feedthroughs which allow the NEG to be heated up to the temperature of 750°C by applying an electric current of about 100 A.

The last point to be clarified was the NEG pump behaviour in real accelerator conditions. How often would the NEG have to be heated to restore its pumping? Would the required heating frequency upset LEP operation?

To answer these questions a chamber equipped with a linear NEG pump was installed in PETRA, an electron storage ring similar to LEP already in operation at DESY (Hamburg). The test was conclusive: the behaviour of the NEG pump was fully satisfactory, leading to its adoption for the LEP project.

About 2000 chambers, most of which were 12 m long, were equipped with a NEG pump as shown in Fig. 7.9. The vacuum pressure after a 24 h baking cycle at 150°C was specified to be less than 2×10^{-9} Pa. Acceptance testing was done in a dedicated laboratory (Fig. 7.11) where many units were tested simultaneously.

At LEP the average pressure in the absence of beams was below 10^{-9} Pa. Pumping of rare gases and methane, at the level of 1% of the NEG pumping, was supplied by locally installed sputter-ion pumps. Fortunately, degassing induced by synchrotron radiation at an electron storage ring decreases with operation due to surface cleaning. For this reason, the frequency of the NEG heating cycles quickly became so low that they only had to be applied when the accelerator was stopped for maintenance.

The NEG pump worked perfectly during the entire ten years of LEP operation.

Fig. 7.11. The test laboratory of the LEP chambers. About 2000 aluminium chambers were tested in batches of 12. Only those providing a pressure lower than 2×10^{-9} Pa after bake-out were accepted.

7.4 Superconducting Skin Boosts Accelerator Cavity Performance

Cristoforo Benvenuti

If the walls of radiofrequency (RF) accelerator cavities are superconducting (SC), the resistive RF losses on the cavity walls are orders of magnitude less than those of normal conducting cavities. However, some power is still absorbed and it increases proportionally to the square of the accelerating field [Box 7.4]. When this field is increased, a value is reached at which the internal surfaces of the cavity exceed the transition temperature T_c (9.3 K for niobium), and the cavity becomes normal conducting (it “quenches”).

Among the various factors which contribute to the temperature of the cavity surface, the thermal conductivity of the cavity wall material plays a major role. Niobium (Nb), the usual SC metal of choice for these cavities, is not a good thermal conductor, and it becomes even worse in the SC state, because the paired electrons do not transport heat. Copper would be a much better choice. Although copper is not a superconductor, it can be coated with a superconducting film [20]. This film does not need to be thick: About 10^{-3} mm would suffice to shield the underlying copper from the RF power. Copper would also provide the additional bonus of a much lower cost.

RF behaviour of superconductors**Box 7.4**

In the presence of radio frequency (RF) fields the electrical impedance of a superconductor (SC) is not zero, as it is for DC applications (e.g. magnets). The reason is that not all the conduction electrons are coupled in resistance-free Cooper pairs, even at temperatures lower than the SC transition temperature T_c . While in DC applications the current carried by the Cooper pairs [Box 8.1] short-circuits that carried by unpaired electrons, in RF conditions the unpaired electrons behave as electrons in a normal conductor and experience resistive losses. The population of normal conducting electrons decreases exponentially with the ratio of the temperature of operation to T_c , so materials with a high T_c represent a better choice. The negative role of the normal electrons is further reduced by choosing metals with low resistivity at low temperature.

While high T_c and low resistivity in the normal state are desired characteristics of a superconductor for RF accelerating cavities, essential practical features are ductility and weldability, required for manufacturing cavities from sheet metal. Niobium (Nb), with $T_c = 9.3$ K, reasonable electrical conductivity and mechanical behaviour similar to that of copper is the most widely used material for this application.

The “figure of merit” Q of an accelerating cavity is proportional to the ratio of the RF power stored in the cavity to the power dissipated resistively on the cavity walls in one RF cycle. At liquid helium temperature Nb offers a Q value about 5 orders of magnitude greater than that of copper. This difference more than compensates for the thermodynamic cost of helium liquefaction and the complexity of cryogenics.

Niobium is a good choice in spite of its very modest critical magnetic field (about 0.2 T) compared to that of the Nb-Ti alloy used for SC magnets (about 14 T). This is because the field of 0.2 T is only reached for accelerating gradients of over 40 MV/m, greater than that needed for circular e^+e^- colliders and linear colliders such as the ILC.

The real limitation of Nb lies in its modest thermal conductivity which defines the temperature gradient through the cavity wall and may result in a cavity “quenching” whenever T_c is exceeded locally. This was the main justification for developing a Nb-coated copper cavity. An added bonus of this approach is that it makes possible the manufacture of cavities using SC materials not suitable for forming from bulk.

For these reasons a vigorous development program was undertaken in parallel to that of the traditional bulk Nb approach in view of exploring the possible use of Nb film technology for the cavities to be used for the LEP upgrade from the initial energy of 50 GeV to about 100 GeV. When this work was started in 1980 little information on thin Nb films was available, and no one had succeeded in obtaining $T_c = 9.3$ K. A deeper analysis showed that all these films had been produced in sputtering systems with poor vacuum (10^{-4} to 10^{-5} Pa). Niobium is very reactive and during coating its purity is spoiled by trapping residual gas molecules. By improving the process vacuum and adopting standard UHV procedures the nominal T_c was immediately obtained on small samples. However, this was only

the first difficulty. Since the cavity is an almost closed vessel of ellipsoidal geometry, obtaining a coating of uniform thickness is far from trivial. Furthermore, the copper surface cleanliness is crucial to ensure good film adhesion. Finally, the coating process requires clean room conditions to avoid surface defects produced by trapping particles floating in the ambient air.

Test cavities were initially coated by bias diode sputtering, which was later replaced by cylindrical magnetron sputtering [35]. The test cavity was a single cell of 500 MHz frequency shown in Fig. 7.12. The cathode was a stainless steel cylinder covered with a Nb liner, from which atoms were sputtered off during the coating by positive ion bombardment. These ions were produced by triggering a discharge in argon or krypton gas at about 10^{-2} Pa, thanks to a negative bias of 400 V on the cathode. The cylindrical cathode contained a solenoid producing an axial field of about 1.4 T at 20 mm from the its surface. This field imparted a circular motion to the discharge electrons, increasing their ionisation efficiency and the sputtering rate. During operation the solenoid was cooled using Freon.

A nice feature of this cathode structure is that by adjusting the cathode diameter and the length of the magnet it is possible to obtain a very uniform coating thickness, because at the cavity equator the higher perpendicular Nb emission compensates for a lower deposition rate due to the larger distance from the cathode.

Fig. 7.12. The sputtering configuration.

Fig. 7.13. The LEP accelerating RF cavity in the cryostat. The cell diameter is 752 mm and the mid-cell spacing is 0.43 m ($\lambda_{RF}/2$).

After the initial development on single cell test cavities, the coating process was applied to LEP 4-cell 352 MHz cavities (Fig. 7.13) quickly exceeding the 5 MV/m field initially specified for bulk Nb cavities, so as to allow the specified field to be raised to 6 MV/m [36]. A total of 288 cavities were produced by three European manufacturers to whom the CERN know-how had been transferred. Finally, these cavities reached very reliably an average accelerating field of 7.5 MV/m, and the LEP energy was gradually increased up to the maximum achieved value of 104.5 GeV [37].

The coating approach could be extended to other materials of superior superconducting properties. Promising results were obtained with Nb_3Sn coating, but it was too late to envisage its application to LEP. These studies have since also been taken over by other laboratories [38].

7.5 Measuring the (Accelerator) World

Michel Mayoud

When commonly speaking of “very accurate measurement” of objects, most people think of metrological control in terms of dimensions and/or position on a bench, and much less of geodesy for describing the earth in terms of measuring angles to within one arc-second, and distances to a few parts in a million. The technology derived from geodesy was also used for micro-geodetic networks as seen in engineering surveys for the construction and deformation control of large objects such as dams. This is why CERN called for geodesists to take care of the sub-millimetre metrology of the PS machine. As accelerators grew and the relative size of the magnet aperture decreased (to contain cost), they required ever tighter positioning tolerances: 0.6 mm for the PS, 0.2 mm for the ISR, 0.15 mm for the SPS, 0.12 mm for LEP; down to 0.01 mm at intersection points, microns for certain LHC components and nanometres for future linear colliders. As in other domains, CERN undertook successive programmes of development, innovating in techniques and instruments for the metrology of accelerators and experiments.

In this vein, prior to tackling the requirements of geodesy at LEP, the team had built up experience and developed a succession of specific devices and procedures for previous accelerators. This included measurement of length using calibrated invar wires; the first application of wire offset measurements, where the offset to a stretched nylon wire was observed with a microscope on a micrometric carriage, providing a simple way to align objects with an accuracy of 0.1 mm; the application of electronics and sensors, and electronic clinometers (developed in-house) [39]. The geodetic reference network for the SPS was measured by trilateration (using calibrated electro-optical devices for the measurement of lengths), with data processed according to a local spherical model. The SPS was the first machine to be housed in a deep tunnel, and a major challenge was to guide the boring machine within the centimetre tolerances imposed by the project. CERN used state-of-the-art commercial gyro-theodolites, gained experience, and acquired widely recognised expertise in underground geodesy.

Nevertheless, given the size and the location of LEP a new chapter in geodesy technology had to be opened. The geometrical tolerances were tighter: The project called for a relative accuracy of 0.1 mm for the alignment of components along the 27 km circumference of the machine and the best possible absolute accuracy (i.e. within a few mm) with respect to the theoretical geometry. While for the SPS the spherical approximation was sufficient to express the effects of the curvature of the earth, for LEP, which lies partly under the Jura mountains, it was necessary to take into account the variation in gravity, in particular the impact on the vertical direction, due to the distribution of mass. This meant that a new geodetic and

geophysical CERN coordinate system had to be defined, into which all accelerator components had to be inscribed. Data were derived from astro-geodetic measurements using accurate zenith cameras (supplied by ETH Zurich), and a precise digital mass model was compiled for integration into the official Swiss model. The data allowed to define the plane on which the 27 km machine was located in measurable space, and was essential for correcting angular and gyroscopic measurements of the underground network used for accurately guiding the tunnelling machines along the 3.3 km sectors between control points. By using the best commercial gyro-theodolite combined with CERN instruments and techniques developed specifically for the task, the azimuthal guiding errors were contained to a radial offset of 10 mm (rms). This geodesy and metrology was also highly dependent on a unique commercial instrument that uses two polarised laser beams (He-Ne and He-Cd) to eliminate first order effects of fluctuations of temperature and pressure of the air, and was designed for measuring long distances with an accuracy of 1 mm at 10 km, the maximum range being about 15 km. By using this tool, the LEP external geodetic network was at the time the most accurate ever obtained for such a size, and was for a while a testing ground for geodesists worldwide [40]. LEP metrology was thus based on well-defined control points — essential for the optimal control of the underground metrological network [41].

A major outcome of a CERN collaboration with IAUB (l'Institut Astronomique de l'Université de Berne) was that millimetre accuracies can be obtained from GPS measurements, when the data is processed with related orbital, atmospheric and ionospheric data from satellite information, combined with local parameters [42].

As concerns instrumentation for the alignment at installation of about 5000 machine components, all CERN instruments were upgraded to allow a full computer-aided alignment process. The metrology of experiments was also significantly improved by designing new complex 3D networks, measured by all available means — with no constraint in setting oblique reference lines or planes in the design. Hydrostatic levels and clinometers were also installed for monitoring height, slope and tilt changes of huge equipment such as the 12 000 t CMS magnet.

It was thanks to the accuracy of the alignment of the LEP collider and a profound understanding of the impact of local geology and global phenomena that effects such as that of the tides described in the next highlight could be clearly evaluated, and that the experiments could record data of far greater precision than anticipated.

7.6 Precise Energy Measurement: Heed the Moon

Albert Hofmann

In LEP the circumference, C , was determined by the orbit passing through the centre of all the quadrupoles, but the effective orbit length of the ultra-relativistic circulating beam was determined by the frequency of the RF system, which fixed the revolution frequency. If C changed by ΔC say, with the frequency kept constant the beam would move transversely in the magnets. This shift would move the beams off centre in the quadrupoles entailing a change in energy $\Delta E/E = \alpha_c^{-1} \Delta C/C$ where α_c is a beam parameter known as the momentum compaction factor. This latter factor was between 1.5×10^{-4} and 4×10^{-4} for LEP, so the energy calibration of the machine was extremely sensitive to geological motion caused for example by tides and variations in the water table which change C [43].

Tides are caused by the variation of the gravitational attraction of celestial bodies, principally the sun and the moon. The tidal forces produce local stretching in the horizontal plane and resulted in a peak-to-peak variation in the circumference of the machine of up to 1 mm. Following these calculations an experiment was performed during a period of full moon, the result of which is shown in Fig. 7.14. Thereafter the information generally available on the tides was put into a model that was used to correct for these effects in the determination of the true energy of the accelerator.

Fig. 7.14. Variation in the energy of LEP beams during a day of full moon. One can see the excellent agreement with the change in energy predicted by the calculation of horizontal strain due to the tides.

In addition to the daily and monthly tidal movements, LEP was also affected by long-term changes in circumference. The movement was observed by monitoring the radial movement of the beam relative to the quadrupoles using the beam position monitors during the annual period of operation of the accelerator for physics. Fluctuations seen during a typical period from May to November are shown in Fig. 7.15, displaying changes of up to 2 mm, a profile found to be very similar from year to year. The diameter tended to be larger during the summer months, and some of the changes were clearly correlated with rainfall. This monitoring of seasonal fluctuations was quite important for the experiments, as the resulting variation in energy was significant, being up to $\Delta E/E = 5 \times 10^{-4}$. Although this did not require the development of new equipment, it illustrates the skill of the operations team in understanding the machine performance in the utmost detail and led to a factor 10 improvement in the determination of the Z mass.

Fig. 7.15. Change of LEP circumference in 1996. A total drift of 2 mm was observed. It gradually increased during the summer, with rapid movements following heavy rain (indicated with arrows).

7.7 The LEP Silicon Vertex Detectors: Right on Target

Hans Dijkstra

After their successful use in fixed target experiments for charmed physics starting in the early 1980s [Highlight 5.9], innovative silicon strip detectors were developed and successfully operated in experiments at colliders like LEP. One major motivation was the study of particles containing heavy flavour quarks, charm or beauty. These particles are short-lived with lifetime τ of the order of 10^{-12} s (1 ps). To tag such particles the transverse accuracy of extrapolation of the tracks of the particle decay to the interaction point (IP) must be better than their characteristic offset $c\tau = 300 \mu\text{m}$. This requires excellent spatial resolution of the detectors, a minimal distance to the IP and minimal thickness of material traversed by the particles. Material affects the direction of the particles, whence deteriorating the extrapolation accuracy. A collider imposes further constraints. The innermost radial position of the detectors is fixed by the radius of the beam pipe, the outermost one by the size of the first tracking chamber. Installation and removal of the complete Si detector system must be possible independent of the other detectors. Layers of silicon strip detectors were arranged in concentric cylinders around the beam pipe. The radius r of the detector wafer, given by the holding frame, provided the r coordinate. The detectors had readout (RO) strips on both sides, parallel (for Φ coordinate) and perpendicular (for z coordinate) to the beam, respectively, allowing space measurements. The RO electronics was normally mounted along two edges of the detector wafer, adding extra material and distributing the heat load throughout the volume of the detector. Solving these problems was a major challenge at LEP, as described here.

A major direction of research addressed the two-sided RO of the Si-detectors. This is made difficult by an e^- accumulation layer at the Si-SiO₂ interface on the ohmic or n-side of the detector, which lowers the inter-strip resistance, hence sharing the charge over many RO strips. The strips must thus be insulated from one another. To disrupt the e^- layer, ALEPH and DELPHI used blocking p^+ electrodes between the n strips. DELPHI used AC-coupled readout strips with a width larger than the n-strip implants, and at a negative potential compared to these implants for insulation.

The ALEPH Silicon Vertex Detector [44] was the first detector operating in a collider to use the two-sided RO. The achieved spatial resolution of the complete device (intrinsic plus alignment) was $12 \mu\text{m}$ in the r - Φ view and $12 \mu\text{m}$ in the longitudinal z view. Two detectors each were mounted onto one electrical building block, the “module”, and two modules were mounted together lengthwise to form the basic mechanical building block of the system, the “face”. The inner layer consisted of 9 mechanically independent faces, the outer layer of 15 faces, making

a total of 2×24 electrically and mechanically identical and independent modules. Each module contained two identical Si wafers, the hybrids with RO electronics and connections. Most components were custom-made.

The design of the detectors was the result of an intense R&D program carried out over several years. It introduced a novel biasing scheme which made it possible to deplete the entire detector volume using only two contacts, one for the p^+ side and one for the n^+ side. Due to the capacitive charge sharing between RO strips, only every fourth p^+ strip on the junction side and every second n^+ strip on the ohmic side were connected to the readout electronics.

With only a modest degradation in terms of material and an acceptable ambiguity level, the RO traces were routed on separate thin substrates. The Z-strips were wire bonded to diagonal RO strips at the edge of the detector, the signals being carried to the electronics in a zig-zag geometry, using additional Z-strips to link the diagonal ones (Fig. 7.16).

The RO chip was a custom-designed with 64 parallel channels arranged in a RO pitch of $100\text{ }\mu\text{m}$ (CAMEX64, CMOS Amplifier with MultiPlexing 64 channels). It was developed in CMOS technology in collaboration between the Max Planck Institut für Physik, Munich and the Fraunhofer Institut, Duisburg. The readout electronics for the Φ and Z-strips of each module consisted of two different ceramic printed circuits equipped with their readout chips and surface-mount components.

DELPHI [45] operated with a silicon strip microvertex detector from the start of LEP in 1989, initially consisting of two concentric layers of single-sided (SS) detectors providing high precision Φ measurements. In 1991 a third layer was added after the installation of a smaller diameter beam pipe. The detector achieved an averaged single hit precision of about $8\text{ }\mu\text{m}$ and a detection efficiency of 98%.

Fig. 7.16. The Z-strips are wire bonded to diagonal RO strips at the edge of the detector. (Courtesy C. Damerell)

The 1994 upgrade of the detector provided 3-coordinate measurements without degrading performance. It used double-sided (DS) detectors with orthogonally oriented RO strips on opposite faces of the detector wafer. In order to maintain the same material thickness, DELPHI developed DS detectors with a second metal layer on the ohmic surface making it possible to read-out the signal from both sides at the same end of the detector. In 1996 a further upgrade increased the solid angle coverage to improve the LEP2 BEH boson searches.

A process was developed using two metal layers, about 1 μm thick, separated by an insulating layer. The first layer coupled capacitively to the n^+ side. Two different approaches to insulate the second metal layer were used in the industrial production: a low temperature deposition of oxide over the whole surface including the metal and an application of a film of Polyimide with an electric permittivity of 0.3 pF/cm. In both approaches tiny holes were opened in the insulating layer, such that the second metal layer, deposited on top could make the desired connections to the first metal layer and the orthogonal readout lines. The top lines ran parallel to the p^+ diodes on the other side of the silicon. In this way all the signals could be read out at a common edge of the detector.

Constructing DS double metal layer detectors with integrated coupling capacitors and polysilicon resistors required 12 to 15 different masks compared with the 5 masks needed for a SS detector. Figure 7.17 shows a perspective view of the structure. Details are discussed in [45].

One more trick was used by DELPHI. Traditionally, the corresponding RO lines of the two detectors forming a half-module were “daisy-chained” together. However, since the RO lines of both sides are at the same potential one can join the n -side of one to the p -side of the other. This so-called flipped module design equalized the noise on the two sides and resolved ambiguities measuring the polarity of the deposited charge.

DELPHI also introduced the first forward pixel detectors at an e^+e^- collider [46].

These few technical details give a taste of the many challenges that were faced in order to optimize the use of this type of detector. Other aspects included cooling, radiation hardness, monitoring of radiation dose, shielding against electrical noise, data acquisition, offline reconstruction and alignment.

The other two LEP experiments, L3 and OPAL, also had excellent micro-vertex detectors [47, 48], while the rival SLD experiment, at the Stanford Linear Collider, used a novel CCD detector concept [49], benefiting from a smaller beam pipe radius. These vertex detectors were essential for all LEP heavy flavour physics.

Fig. 7.17. Conceptual view of the structure of a DS double metal layer detector.

7.8 DELPHI RICH: The Luminous Footprint of Particles

Paul Baillon

Muons and electrons can be identified by their specific interactions with matter. Charged hadrons, however, are frequently identified through their characteristic mass, inferred with a combined measurement of their velocity and momentum. Besides deriving the velocity from time of flight or an energy loss measurement, a powerful method is to measure the Cherenkov radiation [Box 3.2]. When a charged particle traverses a transparent dielectric material (e.g. a liquid or gas) at velocity v greater than c/n (n being the refractive index of the material), it excites the material to emit “Cherenkov” radiation with a characteristic angle θ , where $\cos\theta = c/vn$. Measurement of θ gives the velocity v . Some detectors used this angular pattern to identify hadrons in beams (see CEDAR in SPS chapter). For spectrometers this idea became reality with the insight that gaseous detectors, such as MWPCs [Highlight 4.8] could be made to measure individual photons of the Cherenkov light [50]. The trick is to add certain organic vapours to the chamber gas. These vapours, a favourite being tetrakis-dimethyl-amino ethylene (TMAE), are ionized by Cherenkov light in the ultraviolet spectrum, and the ionization electron is subsequently detected in the gaseous detector. This remarkable invention led to a proposal [51] to build a large 4π quasi-spherical Cherenkov detector around an interaction point (IP), providing a very precise velocity measurement. Conceptually, see Fig. 7.18 (left), the Cherenkov angle would be

measured by focusing the light cone into a ring and projecting it onto the MWPC. A rather crude momentum measurement would suffice for an adequate detection of the particles. This concept was as elegant as it was revolutionary at the time. It led however to a more realistic, yet still very ambitious incarnation at the LEP experiment DELPHI, the Ring Imaging Cherenkov, RICH [52]. The isotropic sphere was replaced by a more conventional geometry, a cylinder (Barrel) and two end caps (EC), which could be integrated in an otherwise classical spectrometer. It represented a major advance in experimentation, allowing hadron identification in most directions around the IP.

RICH at DELPHI

The measurement of the velocity is most sensitive close to the threshold of light production, where the angle varies rapidly with momentum. To cover a range of momenta, one should use several detectors with different indices. As a compromise, the Delphi RICH (Fig. 7.18, right) had two radiators, one liquid and one gaseous. Between them, a single Drift Tube (DT), a TPC with quartz windows, detected both the photo-electrons (PE) from Cherenkov light coming directly from the liquid, and that focused back from the gas by parabolic mirrors. An electric field in the DT caused the PEs to drift along its length of 155 cm to MWPCs. Wire and cathode pads gave two coordinates. The third came from the drift time between beam collision and PE detection, the drift speed being known.

In the following the main technological challenges are discussed with emphasis on the Barrel RICH, developed and built at CERN. For the Forward RICH see [53].

The Drift Tube was the heart of the RICH. Designed along the ideas of [50], it used the property of TMAE to emit a free electron when hit by an ultraviolet photon (> 6 eV). Its vapour pressure (about 100 Pa at 40°C) is sufficient to absorb most of the photons within 2 cm. The range of effective wavelengths imposed the use of quartz windows and adequately transparent fluids. To achieve the necessary drift conditions, a very homogeneous electrical field of 530 volt/cm was generated by applying a voltage of up to 80 kV on conductive chromium strips (0.1 mm) surrounding the quartz windows at a pitch of 6 mm. Chromium was evaporated in a large vacuum bell from a bloc heated by an electron beam and reached the quartz windows through an appropriate and precisely positioned mask. A conductive paint ensured connection between quartz faces. In the drift gas (75% methane, 25% ethane), the drift velocity was 6.67 cm/ μ sec. A challenge was the purity of the mixture — it had to exclude any electronegative gas capturing electrons, such

Fig. 7.18. Sketch of RICH. Left: the principle. Right: barrel RICH of DELPHI.

as oxygen, which also destroys TMAE. The liquid radiator, 1 cm of C_6F_{14} (index 1.28) was contained in a box, closed on one side by a quartz window, 12 cm away from the first DT, and on which copper wires with a 6 mm pitch were positioned to improve the homogeneity of the field in the DT. The Cherenkov light propagated in the liquid over about 1 cm, coaxial with the particle direction, and with a maximum opening angle of ≈ 670 mrad. This cone refracts when entering the gas space and intercepts the DT along a figure depending on the incidence angle.

Measuring the resulting PEs (typically 12) gave the Cherenkov angle in the liquid with a precision of $\sigma \approx 5$ mrad. Due to the chemical activity of freon, with time, the pipes of the filling system lost some tightness and liquid was leaking into the gas. A distillation plant was built to separate the fluids, such that the RICH could operate successfully up to the end of LEP.

After the DT, particles crossed a gas radiator of ≈ 40 cm of freon gas C_5F_{12} (index 1.0018 at 1 bar), emitting Cherenkov light at a small angle (maximum opening ≈ 62 mrad). The light was reflected back by parabolic mirrors and focused onto the DTs, resulting in an almost circular ring pattern of about 2.4 cm radius and with typically 8 PEs. The required accuracy on the Cherenkov angle was about 5 mrad rms per PE, to which various sources of error contributed roughly equally. Therefore, mirrors with an optical quality in the mrad range were adequate. Optimally, the focal point of the mirrors should be on the DT, with close to normal incidence, which minimizes various errors. Off-axis parabolic mirrors were thus needed. Best achievable reflectivity in the UV was mandatory as was a very smooth reflecting surface to avoid diffusion, with a local deviation from smoothness of rms < 1.6 nm. Ordinary glass pane obtained by the industrial floating technique has an rms of 0.2 nm. Thus the RICH mirrors were made of 6 mm thick float glass, slumped on a parabolic mould machined on a precision lathe. The glass plate, cut to the correct circular shape, was placed in a large oven. The top of the mould was heated at 610°C and the air below it was evacuated, so

that the glass would accurately adopt its shape. Once so shaped, the glass plate was cut to the desired dimensions and coated under high vacuum with pure aluminium (80 nm) protected by a layer of MgF_2 (30 nm). The average reflectivity achieved in the UV was 80%. This technique, pioneered by the inventors of the RICH [50] and developed at CERN [54, 55], was transferred to industry, which produced 300 mirrors for the Barrel RICH.

Given their quality, the mould was later used to make 18 mirrors for an astroparticle experiment in the Pyrenees. They focused the Cherenkov light produced by very energetic γ rays showering in the upper atmosphere. These γ rays are emitted by a neutron star, a remnant from a star collapse observed 1000 years ago, located in the CRAB nebula [56].

The success of the RICH (Barrel and EC) during a decade of DELPHI data taking was to allow to identify hadrons over a wide momentum range. Figure 7.19 illustrates the complementarity between the RICH identification (left) and that obtained from the ionisation measurement in the DELPHI TPC at lower momenta (right), and see Box 5.2. The DELPHI RICH initiated the development of similar instruments, e.g. those at LHC [Highlight 8.10].

Fig. 7.19. Left: The RICH identification by Cherenkov angle in liquid (a) and gas (b) versus momentum. From left to right, pions, kaons and (anti-)protons curves. Right: DELPHI TPC identification via measurement of dE/dx .

7.9 BGO for the L3 Experiment: Betting on Precision

Paul Lecoq

At the time the LEP programme was launched the top quark had yet to be discovered, and its mass was expected to be within the energy range of the collider. The electromagnetic calorimeter of the L3 experiment was therefore designed to achieve the best possible energy resolution down to 100 MeV in order to explore the detailed spectroscopy of the toponium system, the putative bound state of the top–antitop quarks. A similar situation had been encountered a few years earlier, after the discovery of the J/ψ , the charm–anticharm bound system, by B. Richter and S. Ting (also spokesman of L3): the high precision study of charmonium states took advantage of the unprecedented performance of the thallium-doped sodium-iodide (NaI(Tl)) Crystal Ball at PEP. This success convinced the community that a homogeneous crystal-based electromagnetic (e-m) calorimeter would be the best way to achieve good energy resolution in the 100 MeV to 10 GeV energy range. Indeed, one hallmark of the L3 concept was the state-of-the-art performance of the calorimeter in terms of energy and angular resolution for photons and electrons over this wide energy range.

The L3 collaboration “put its money” on a recently discovered crystal, bismuth germanate (BGO). This material had been known as a scintillator for less than ten years [57]. In 1983 measurements in a test beam at CERN had demonstrated that BGO, with PIN silicon photodiode readout, had excellent properties as a homogeneous e-m calorimeter [58]. The reason for the choice of BGO was motivated by the much higher stopping power for photons and electrons compared to NaI(Tl). This meant that a compact, highly granular and high performance calorimeter could be built with minimum impact on the dimensions and cost of the external detectors (hadron calorimeter and muon spectrometer). Moreover, besides having good scintillation properties, BGO is not hygroscopic, unlike NaI(Tl).

The calorimeter was installed in a 0.5 T solenoidal magnet of almost 10 metres in diameter, and surrounding a high precision vertex detector [Highlight 7.7]. It consisted of nearly 12 000 BGO crystals with readout provided by photodiodes insensitive to magnetic field. It was composed of a cylindrical barrel with 7680 crystals and two endcaps of 1536 crystals each in a pointing geometry with a small offset of 10 mrad to avoid photon leakage in the gaps between crystals. Each 24 cm long crystal had the form of a truncated pyramid, about $2 \times 2 \text{ cm}^2$ at the inner face and $3 \times 3 \text{ cm}^2$ at the exit.

Transforming the BGO crystal from laboratory curiosity to mass-producible technology meeting the stringent L3 experimental specifications required a new style of R&D. A large-scale multidisciplinary effort had to be organized, a novelty for detector R&D in high energy physics. This involved a number of institutes of

the L3 collaboration, but also experts in crystallography, solid state physics and luminescence. A decade later this same collaboration would become the seed of the Crystal Clear collaboration, which made major contributions to the development and construction of the Lead Tungstate based calorimeter of the CMS experiment at the LHC [Highlight 8.8]. As a result of this effort (and thanks to the contacts of the L3 spokesman), technology for the mass production of BGO was developed at the Shanghai Institute of Ceramics (SIC), where 12 000 BGO crystals of excellent and reproducible quality were produced over a period of three years with monthly batches of 130 to 400 crystals.

The 10 t of germanium oxide needed for this production were provided as an in-kind contribution to the experiment from the strategic reserve of the former Soviet Union. The bismuth oxide was provided by China. The very pure bismuth and germanium oxides (impurity level $< 10^{-6}$) were carefully mixed in the correct stoichiometric proportions. The resulting polycrystalline powder of $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) was then poured into a platinum foil, folded and welded in the shape of the crystal (trunk of pyramid) and only slightly larger than the final crystal to minimize the losses at the mechanical processing phase. These crucibles were introduced vertically in an oven for growing the crystal, with a small seed crystal in contact with the powder. After heating-up the crucible at a temperature slightly higher than the BGO melting point (1040°C) a temperature gradient was slowly displaced along the crucible from the seed to the end. The long term stability of the electricity supply was crucial, and the interest of the Shanghai authorities in the project certainly helped in ensuring it was stable.

An accurate ($\approx 50 \mu\text{m}$), fast, cheap and safe method for cutting and polishing the crystals was developed at CERN and transferred to SIC. Diamond disks were used to saw the ingots to the required dimensions. The surface finish was good and reproducible enough to proceed directly to simultaneous mechanical polishing of nine crystals on a spinning table. Automatic mechanical and optical characterization benches were also developed at CERN and installed in Shanghai for systematic evaluation of all crystals prior to shipment. The yield of the crystal growth procedure was over 99%.

Because of the 0.5 T magnetic field the BGO crystals could not be read out by regular photomultipliers. Instead, two 1.5 cm^2 PIN photodiodes with high (70%) quantum efficiency were glued to the rear face of each crystal. The absence of gain and stringent requirement of good resolution at energies down to 100 MeV imposed severe constraints on noise in the readout electronics. A charge sensitive amplifier was mounted directly on the back of the crystals, using a low noise FET in cascade mode, with an output rise time (300 ns) matching the decay time of BGO scintillation.

Material in front of and between crystals was minimized by using carbon fibre honeycomb material, an audacious choice at that time (see Fig. 7.20). Support was provided by thin (200 μm) carbon fibre-epoxy walls between crystals and a cylindrical inner tube coupled at each end of the barrel to a conical funnel, which carried the 10 t weight of the full barrel calorimeter at four bearing pads. The light yield of BGO depends on its temperature (-1.55% per $^{\circ}\text{C}$), so the mechanical structure also featured a complex cooling and thermal regulation system to remove heat produced by the front end electronics close to the crystals, and stabilize the temperature to within 0.5°C . This unique calorimeter, the success of a very large world-wide collaboration, achieved the original design goals: low energy 100 MeV photons could be measured with 5 MeV precision, high energy photons in the region of 10 GeV to better than 1% [24].

The mass production of BGO became a mature technology so that the excellent properties of this crystal could be exploited in other domains, such as nuclear and space experiments, as well as in medical imaging devices, where BGO became the crystal of choice for the second generation of PET scanners for about two decades.

BGO is now progressively replaced by LSO (lutetium orthosilicate), a crystal discovered in the 1990s, having a higher light yield and a shorter decay time.

Fig. 7.20. The BGO calorimeter barrel during assembly at CERN.

7.10 The Magnetic Cavern of L3

Alain Hervé

The L3 detector was designed to measure with unprecedented accuracy and resolution electrons, photons and muons produced in the particle collisions. These particles passed through a sequence of detector systems where they were tracked and identified according to their characteristic signatures: the vertex-chamber, the electromagnetic calorimeter, the hadronic calorimeter and the muon chambers. This mission called for a highly specific architecture of the detector, in particular the experimental hall, the unconventional magnet, the muon system and the support of the system of inner detectors surrounding the beam pipe at the collision point [24] (see Fig. 7.21).

The original idea was to integrate the magnet yoke into the rock of the cavern, whence the name “magnetic cavern” which would stay with L3. Finally, it was decided for ease of maintenance of the muon chambers and to access equipment with a travelling crane to increase the size of the cavern. The 21.4 m diameter, 26.5 m long experimental hall is oriented longitudinally along the LEP beam line that enters the hall with a slope of 1.39%: the complete detector is inclined to follow this slope. A 23 m diameter and 52 m deep access shaft connects to one end of the experimental hall, for installing experimental equipment. After the installation of the major large components the shaft was used for the installation of experimental services (water, cables, gas, ventilation, etc.), and as technical space for installing power converters, cryogenics, monitoring equipment and offices.

Observing muons with state-of-the-art momentum resolution was one of the L3 priorities: an important ingredient was the largest magnet ever built for a particle physics experiment. The octagonal shaped magnet has a yoke consisting of 6400 t of low carbon steel and an 1100 t aluminum coil. Given the size of the coil, it was built from individual octagonal aluminum sections, each one being built at CERN. These sections were subsequently integrated into the yoke. A current of thirty thousand amperes in the aluminum coil generated a uniform field of 0.5 T. The magnetic circuit of the octagonal yoke had to be closed with massive iron endplates. These endplates, each weighing 700 t, were split in the middle and could be opened like doors to give access to the muon detectors for maintenance. The magnet is lined with an active thermal screen providing a thermally controlled environment to the particle detectors. The yoke rests on a concrete cradle integrated in the floor of the detector hall.

Fig. 7.21. Overview of the L3 detector [24].

Inside the magnet precision Muon Chambers were arranged in three concentric layers, to measure the trajectories of muons in the magnetic field over a volume of 1000 m^3 . To achieve the design momentum resolution these chambers were built with mechanical tolerances of $30 \text{ }\mu\text{m}$ over an area of $3 \text{ m} \times 6 \text{ m}$. Sixteen octants of muon chambers were supported on two support tubes. Several precision straightness monitors, using LEDs and quadrant photodiodes were specially developed to ensure accurate mutual alignment of the chambers within an octant. At the time this muon system was the most advanced of its kind: its success encouraged the LHC collaboration ATLAS to adopt the concept and take it to the next level of dimension and performance [Highlight 8.12].

The 300 t support tube, 30 m long and 4.45 m in diameter was another rather daring innovation that contributed to the performance of the muon spectrometer. It passed through the magnet coaxial with the beam line. It rested on continuously adjustable servo-controlled jacks placed on concrete pillars. The part of the support tube inside the magnet was of non-magnetic stainless steel, the remaining portion in carbon steel. In this way the support tube rendered all detector systems (600 t in total) mechanically independent of the magnet.

The hadron calorimeter measured the energy of elementary particles, jets of particles, and contributed to muon identification [Box 3.2]. It consisted of 300 t of depleted uranium plates sandwiched between some 8000 proportional chambers.

The electromagnetic calorimeter was another “world première”, designed to measure the energies and positions of electrons and photons from 100 MeV to 100 GeV with high resolution [Highlight 7.9].

Charged particles were tracked in the time expansion chamber which had to be of limited radius to fit inside the BGO calorimeter. It featured an interesting variant of the MWPC [Highlight 4.8] measuring tracks with 40 μm accuracy in a volume of one cubic metre. At the beginning of 1991, the radius of the LEP beam pipe was reduced from 8.0 cm to 5.5 cm. L3 took advantage of this extra space by installing a Silicon Microstrip Detector (SMD) to upgrade its central tracking capability.

The L3 experiment was an important precursor to the LHC experiments. The precision crystal electromagnetic calorimeter was a precursor of the CMS electromagnetic calorimeter [Highlight 8.8]. The alignment of muon chambers using optical systems was further developed for the ATLAS muon spectrometer.

L3 was the only LEP experiment installed stationary at the interaction point (as is the now case for the LHC experiments). The other LEP experiments were assembled adjacent to the accelerator, to be pulled in and out on rails so that LEP could continue to be operated if an experiment required extensive maintenance. New procedures for installation and maintenance had to be developed to take into account the interaction with the machine. To gain time in the installation sequence, heavy parts of the detector, such as the support tube and the hadron calorimeter barrel (weighing each around 300 t) were completed in the surface hall prior to installation in the cavern using rented heavy lifting equipment. Following this experience, the same technique was used extensively for the CMS experiment.

The L3 experimental area and large magnet has been reused to house the ALICE LHC experiment. This was a magnificent legacy, allowing L3 infrastructure to be re-used, in true CERN fashion, for ALICE, a state-of-the-art experiment dedicated to the study of heavy ion collisions at the highest possible energy.

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