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Designing and Building LEP

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Abstract

The evolution of the concept and design of the Large Electron-Positron (LEP) storage ring between 1975 and 1989 is summarized. The development of the key components based on novel ideas is described and the performance of LEP at the different operational phases from the year 1989 to 2000 is outlined.

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1. Introduction

Studies started at CERN in 1975 to investigate the range and feasibility of experiments which could be done with a very high-energy e^+e^- storage ring. The context was that of a European facility with a physics reach beyond existing storage rings. These studies lead to many iterations between the desiderata of the physics community, the technical feasibility and cost studies until 1981, when the final proposal was presented to the CERN Council.

The proposal (LEP 1) was to construct an e^+e^- storage ring of 27 km circumference with four collision points and an initial beam energy of about 50 GeV, sufficient for the production of the then hypothetical neutral boson Z^0 . The storage ring was designed to have the potential to eventually reach a beam energy of about 100 GeV with a superconducting radio-frequency (rf) system yet to be developed. The magnets were designed for a beam energy of 125 GeV.

Council approved the project in December 1981. After seven and a half years of construction, the first beam collisions took place in summer 1989 at a beam energy of 46 GeV, corresponding to the peak of the Z^0 production. The luminosity was increased rapidly, and reached half the design luminosity in 1990. Operation at the Z^0 was continued until 1995 when the upgrading to higher energy started.

Research and development of superconducting rf accelerating structures already started in 1979, and from 1995 the energy could be raised in steps, as imposed by the industrial production schedule of these structures and the available shutdown time for installation. In 2000, LEP 2 reached its maximum beam energy of 104 GeV and was shut down at the end of that year. It was dismantled in the years 2001 and 2002 in order to make place for the Large Hadron Collider (LHC), which will be installed in the LEP tunnel.

Complementing previous accounts which emphasize different aspects [1, 2], this paper retraces the evolution of the LEP 1 and the LEP 2 concept and of those key components which were based on novel concepts. The performance achieved at the Z^0 and at the highest energy is briefly reported.

The second chapter covers the evolution of the basic concept until the final design for LEP 1. It describes the iterations in the choice of the site and general layout, the construction of the tunnel with the associated civil engineering, and the installation. The third chapter summarizes the R&D of the superconducting accelerating structures, and covers the evolution of the upgrade concept and its implementation in the framework of the LEP 2 programme.

2. LEP 1 Design and Construction

2.1 Evolution of the Design

Studies for a high-energy e^+e^- storage ring for colliding beam experiments started at CERN in 1975. A year later, a cost optimisation procedure and a first outline of such an e^+e^- collider with a centre-of-mass energy of 200 GeV were presented [3], and two Study Groups were set up: one investigated the range and feasibility of experiments with high-energy e^+e^- colliders and the other studied the technical feasibility of such a facility. The report by the first group [4], which mainly investigated the scope and nature of physics, contains also the preliminary findings of the accelerator group which by that time had reached roughly the half-way point in its study.

The second group published its results in 1977 [5]. The study had been based on the assumption of a beam energy of 100 GeV and a luminosity $10^{32} \text{ cm}^{-2}\text{s}^{-1}$. The circumference was 52km, about the optimum for a storage ring equipped with room-temperature radio-frequency (rf) accelerating cavities. The rf system considered had already many features of the final design such as 5-cell coupled cavities driven by klystrons operating at 350 MHz. However, no satisfactory engineering design could be found for the vacuum and magnet systems to cope with the low bending field at injection and the gas load due to desorption by synchrotron radiation. Also, simulations of the beam orbits indicated that beam stability would be very difficult to achieve. A first cost estimate was worked out assuming geological properties as found during the construction of the Super-Proton-Synchrotron in the Geneva basin near CERN but no specific location was suggested. In order to facilitate comparison with later versions, selected key parameters are given in Table 1.

Since this design presented a number of unresolved problems and the construction cost appeared excessive, a new design of a smaller ring (22 km circumference) with the nominal beam energy reduced to 70 GeV but the same luminosity was initiated. The key parameters are included in Table 1. This time, viable engineering solutions for the vacuum and magnet system were found. The vacuum chamber was made from extruded aluminium which included a water cooling channel to remove the heat deposited by synchrotron radiation emitted by the beam, and a channel for distributed sputter-ion pumps in the dipole magnets. The dipole magnets were made from stacks of steel laminations powered by a single-turn coil made from extruded aluminium. Storage cavities coupled to the accelerating cavities were considered in order to reduce the rf power dissipation. Superconducting cavities would provide an average accelerating field of 3 MV/m for a possible upgrade to 100 GeV. The rf systems were located in dispersion-free straight sections symmetrical around the eight interaction points. Since the latter were equipped with access shafts, the rf systems profited from the proximity of access, communications and feed-points for power and cooling water. For the first time, a site was proposed for LEP, guided by a recommendation of the European Committee for Future Accelerators (ECFA) that LEP should be built close to the CERN site. The ring was located such that it nearly touched the SPS to the NNE in the plan view, to keep the option open for colliding the protons in an SPS by-pass with the leptons in LEP. One of the main conclusions of the design study [6] was that LEP appeared technically feasible.

This design was discussed in a LEP Summer School [7] and in two meetings of the ECFA/LEP Working Group. The main conclusion was that a somewhat larger machine, in which the energy required for useful W pair production could be guaranteed with room-temperature rf cavities, would be desirable. In addition, several suggestions for improvements had been made. The new design study [8] considered a ring of 30.6 km circumference and the nominal energy of 86 GeV could be reached with room-temperature cavities only. A later installation of superconducting rf cavities with 5MV/m would provide a maximum energy of 130 GeV in stage II. Table 1 gives the important parameters. The vacuum system was similar to the previous version but assumed in-situ glow-discharge cleaning and bake-out to achieve the desired base pressure and minimize desorption from synchrotron radiation. A novel design of the core of the 5.7m long dipole magnets with a steel-filling factor of 0.27 was proposed taking account the unusually low bending field (0.12 T) even at 130 GeV. The injector chain was based on a slow-cycling 22 GeV synchrotron re-using the ISR magnets. For the rf system, the use of storage cavities was definitively adopted. The proposed location of LEP was further south with only 1/3 of the tunnel in limestone and the rest in the well-known molasse of the Geneva basin. The ring was tilted by 1° relative to the horizontal plane to minimize the depth of the shafts while keeping the tunnel in competent rock. In the plan view, LEP had the SPS inside its foot-print, nearly osculating the SPS on the SSE side of the latter.

With the feasibility of LEP well established, discussions with the CERN Council in preparation of approval started in 1980. In order to be able to build LEP within the existing CERN resources, a stripped-down version was presented to Council. The ring had only 27 km circumference and, instead of eight caverns for detectors, only four which could be dug without access tunnels. A new location was proposed, further minimizing the depth of the shafts and the part in the limestone, but still close enough to the SPS for ep collisions. The rf system was substantially reduced for this Phase 1 (LEP 1) but still sufficient for a nominal beam energy of about 50 GeV, enough to cover the expected Z^0 resonance. Only two straight sections were equipped with rf cavities instead of eight.

Table 1, Evolution of key parameters

Date [ref.]		1977 [5]	1978 [6]	1979 [8]	1984 [10]
Beam energy	GeV	100	70	86	55
Circumference	km	51.5	22.2	30.6	26.7
Luminosity	$\text{cm}^{-2}\text{s}^{-1}$	1.2×10^{32}	1.0×10^{32}	1.1×10^{32}	0.16×10^{32}
Number of experiments		8	8	8	4
RF voltage	GV	1.72	1.24	1.95	0.40
Active rf length	km	2.47	1.34	1.63	0.272
RF power	MW	109	74	96	16

To reduce the cost further, it was proposed to use the existing synchrotrons of CERN, equipped with a new pre-injector, as LEP injector chain. This had the advantage that the LEP Programme could be presented as an extension of the Basic Programme of CERN.

The CERN Council authorized the construction of LEP 1 in December 1981.

Although construction of components started immediately after approval, the project team made a number of improvements and optimisations in the following years. The Design Reports of the injector chain [9] and for the LEP main ring [10] reflect this final evolution and virtually describe LEP as it was when commissioned in 1989 [11]. Table 1 gives the main parameters.

2.2 Main Systems

The magnet lattice had a four-fold symmetry with eight straight sections which were symmetric around the interaction points in their center. Since the beams consisted initially of four equidistant bunches of electrons and positrons, they crossed in eight points. The beams collided only in the interaction points P2, 4, 6 and 8 which were equipped with special quadrupoles, focusing the beam to the required transverse size, and detectors. The beams were vertically separated in the remaining four points by means of electrostatic separators [12]. The chain of dipole magnets formed octants between the eight straight sections. Basically, the four superperiods formed an octagon with rounded corners, with reflection symmetry around all crossing points.

A large number of dipoles, quadrupoles, sextupoles and dipole correctors formed the magnet system. The most remarkable elements were the dipole magnets covering in total 19 km. They had 5.75 m long C-shaped steel-concrete cores composed of a stack of low-carbon steel

laminations, 1.5 mm thick, separated by 4 mm gaps filled with cement mortar (Fig. 1). Four pre-stressing rods acted on two end-plates compressing the core. This novel design provided cores of high stiffness in torsion and flexion at a price about half that of a core made only from steel [13].

Fig. 1 - Steel-concrete core of the dipole magnet

The dipoles were excited by means of long bars made of extruded aluminium, again a considerable saving compared to traditional coils. Other remarkable developments were the eight warm-bore, iron-free superconducting quadrupoles situated closest to the four detectors in order to achieve a minimum vertical beam size at the collision point [14] and the various wiggler magnets [15, 16] for fine-tuning of the beam parameters.

The vacuum chamber of extruded aluminium was now covered with a lead radiation shield and three water-cooling channels, a design compatible with the highest energies (Fig. 2).

Fig. 2 - Vacuum chamber section made of (1) extruded aluminium profile with the elliptic beam channel, three cooling water ducts (2) and surrounded by a 3.8 mm thick lead shield (3). The NEG pump (4) is housed in a separate pump channel connected to the beam channel by a row of longitudinal slots (5)

The strong desorption of gas from the walls struck by synchrotron radiation required a distributed pumping system. Since the bending field in LEP was below the threshold of the usual linear sputter-ion pumps to operate inside the dipoles, a non-evaporable getter (NEG) [17] pumping system was used for the first time in LEP. A constantan strip covered by cold sintering with a Zr-Al alloy was located in the pump channel [18]. After commissioning, the vacuum system provided pressures in the low 10^{-8} Pa range in the presence of circulating beams. The lifetime due to beam-gas interactions was longer than the required 20 h [19].

The rf accelerating system was installed on either side of P2 and P6. It consisted of 128 standing-wave Cu cavities operating at room-temperature and at 352 MHz. The accelerating cavities were 2.125 m ($5\lambda_{rf}/2$) long and made up from a string of five resonant cells magnetically coupled by slots operating in π -mode for acceleration. Each of the cavities was coupled to a single-cell, spherical storage cavity operating in the lowest H-mode, a mode having vanishing electric fields on the walls and, therefore, very low losses (Fig. 3). This coupled system provided a reduction by a factor of 1.5 in power dissipation for a given accelerating field [20]. The cavities could provide an accelerating field of 1.5 MV/m when powered by 16 klystrons each providing 1 MW. However, a gradient of 0.6 MV/m was sufficient for operation at the Z resonance. This provided a large engineering margin in the first years of operation and resulted in very reliable operation.

Fig.3 - rf cavity assembly

Other important systems were the various devices for beam observation [21], the power converters [22], controls and those which were part of the infrastructure such as cooling, ventilation, electrical power distribution and access control [10].

2.3 Civil Engineering and Installation

Eighteen shafts between 5 m and 23 m in diameter and between 50 and 140 m deep had to be sunk to the level of the machine tunnel. Excavation of the tunnel was done with full-face tunnelling machines in the molasse. Three of these machines were used in parallel achieving an average speed of 25 m per day and machine. In the limestone, slower drill-and-blast techniques, combined with advanced test borings had to be used because of the risk of water in-rush. The concrete shell of the tunnel in the limestone was dimensioned so as to withstand more than 15 bars of water pressure, corresponding to the height of the rock overburden. A variety of roadheader-type machines were used for the excavation of the caverns almost all of which could be located in the molasse [23]. About 70 surface halls had to be built near the

access shaft for housing the services. Civil engineering started in 1983 when both Host States had given the construction permission. By 1985, all shafts had been dug, and tunnelling was finished at the beginning of 1988.

In order to guide the tunnelling machines and to align the collider components to millimetre-precision on the scale of kilometres, advanced survey methods had to be applied [24]. A surface network with baselines of up to 13 km length was established which were measured with 10^{-7} precision with a laser interferometer. The tunnelling machines were guided by laser beams so that the tunnel was closed with a deviation of only 1 cm. The positions of the machine elements in the tunnel were determined by a chain of quadrilateral figures between two crossing points so that adjacent quadrupoles in the magnet lattice could be aligned to better than 0.1 mm.

Installation started in the middle of 1986 and was terminated in June 1989 when the tunnel was closed for “Controlled Access” in preparation of the start-up.

2.4 Commissioning and Performance at Z^0

Positrons were injected in the first LEP octant in July 1988, concluding the running-in of the injector chain which had started in 1986 with tests of the electron linac. This also provided a test of the SPS-LEP beam transfer, the LEP injection system and the optical properties of the first octant.

The whole LEP ring was ready to take beam on 14 July 1989 when the first beam was injected and circulated within one hour. The first collisions took place one month later [25]. By the end of the run in 1989, one third of the design luminosity ($1.1 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ at 46 GeV) had been reached and an integrated luminosity of 1.7 pb^{-1} per experiment corresponding to a total of 100000 Z^0 events had been delivered.

For higher luminosity, the number of equidistant bunches was increased from 4 to 8 per beam in 1993 and, eventually, the luminosity exceeded the design luminosity by **50% in this year**. Since bunches then had to be separated in addition in eight mid-arc points, ten additional separators had to be installed. The separators generated a vertical electric field deflecting positrons and electrons in opposite vertical directions. By the use of sets of these devices appropriate closed-orbit bumps were created so that bunches of opposite polarity passed each other without colliding. In 1995, the last year of operation at and close to the Z resonance, the number of bunches was increased from eight to twelve, resulting in a further increase in luminosity to $2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. In order to avoid unwanted crossing and to limit the number of separators, bunches were no longer equidistant but grouped in four equidistant trains of three bunches each per beam.

A number of challenges in accelerator physics [26] had to be mastered in these years of operation at relatively high beam currents and a relatively low beam energy but continuous improvement in beam observation, collimation, power supplies and controls, use of feedback systems finally lead to a total integrated luminosity of 206 pb^{-1} around the Z resonance since the start-up in 1989 [1].

In order to measure precisely the mass of the Z^0 and the width of the resonance, the beam energy had to be calibrated with high precision at each step during scanning across the resonance. The most precise method was the measurement of the average beam energy by resonant depolarisation which reduced the contribution of the uncertainty in beam energy to $1.7 \text{ MeV}/c^2$ on m_Z and $1.3 \text{ MeV}/c^2$ on Γ_Z [27]. The large amount of data and the precision of

the method unveiled many subtle effects which were influencing the LEP beam energy at the 10^{-4} level as e.g. the perturbation of the magnetic field hysteresis by leakage earth currents from electric trains circulating on a nearby railway line, energy deviations due to circumference variations brought about by geological movements due to earth tides and hydrological strains [26].

3. Upgrade to LEP 2

3.1 Development of superconducting rf cavities

Based on the experience from the development of superconducting rf particle separators, a development programme aimed at the series production of superconducting (sc) cavities was initiated at CERN in 1979, starting from single-cell cavities made from bulk Nb. It was soon extended to produce standing-wave cavities of 1.7 m active length ($2\lambda_{\text{rf}}$), consisting of a string of four cells coupled through the beam hole and operating at 352 MHz in π -mode, a concept which was also adopted for series production. Two lines of development were followed: the first based on Nb sheets of improved thermal conductivity; the second relying on Nb-film obtained by sputtering on Cu sheets.

At the time of approval of LEP1 it appeared unrealistic to propose sc cavities given their development status. However, the use of this technology was firmly foreseen for the energy upgrade leading to LEP 2. Various scenarios were developed envisaging beam energies up to 90 GeV in order to reach the threshold of W pair production with 192 sc cavities [28]. A number of technologies had to be developed such as He cryostats, internal electron-beam welding, chemical treatment of 4-cell cavities, dust-free rinsing, and assembly with couplers and to modules containing 4 cavities. When the official upgrade programme started in 1987, 4-cell cavities of both designs produced in tests about 7 MV/m average accelerating fields with quality factors of better than 3×10^9 at a He temperature of 4.2K. Figure 4 shows a sc cavity in a module.

Fig.4 Superconducting rf cavity in cryostat and module

3.2 Construction and installation

Construction started with the first order for 20 Nb-bulk cavities placed in 1989 in industry followed by a contract for 160 Nb-film cavities which turned out to have inherent advantages such as better thermal stability against quenching, savings on Nb material, insensitivity to

stray magnetic fields, higher quality factor, and the potential of replacing the Nb coating with a better one in the future [29]. For this reason, only four modules containing 16 Nb-bulk cavities were finally used in LEP, all the others were modules with Nb-film cavities.

The upgrade to LEP 2 [30] required modifications to many other systems. Since the new rf system had to be installed also in the straight sections around the interaction points 4 and 8, new klystron galleries had to be dug and equipped with klystrons feeding eight sc cavities and their modulators, control and ancillary equipment. The power supplies of the magnets had to be upgraded and four large cryogenic plants (4×12 kW at 4.5 K) with associated He transfer lines had to be installed. From 1997 onwards, the cryoplants had been upgraded with a view to their future use for LHC so that a total cooling power of 53 kW at 4.5K was available, which was imperative for operating the Nb-film cavities beyond the nominal 6MV/m as required for operation at ≥ 100 GeV. The layout of the magnetic elements in the rf sections had to be modified and new beam collimators installed. In order to be able to focus the higher energy beam in the detectors at the four collision points, ten new superconducting quadrupoles had to be manufactured and installed together with numerous other auxiliary equipment.

Installation of cavities assembled in modules started in 1990 but was halted in 1992 when problems with the power couplers were discovered. After remedies [31] had been found by 1994, installation resumed and continued until the beginning of 1999, as can be seen from Fig. 5. The last modification of the rf system occurred in the winter of 99/00 with the reinstallation of eight additional room-temperature cavities mobilizing all possible reserves to increase the beam energy. In the final configuration in the year 2000, 288 four-cell sc cavities having an active length of 490 m and 56 room-temperature cavities, powered by 43 klystrons of 1 to 1.3 MW nominal power, provided a peak rf voltage of 3.6 GV [32, 33].

Fig. 5 - Installation history of modules each containing four superconducting rf accelerating cavities

If LEP had been fully equipped with Nb-film cavities, replacing all Cu and Nb-bulk cavities and using all the available space in the straight sections without any further civil engineering work, 384 Nb-film cavities could have been installed providing a peak rf voltage of 4.8 GV.

3.3 Performance

Figure 6 shows the evolution of the available rf voltage and the beam energy of LEP 2 over the years [\[1\]](#).

Fig. 6 - The evolution of beam energy, available and nominal rf voltage

The increase in voltage up to 1999 was brought about by adding sc rf cavities operating around their nominal value of 6 MV/m. Later, in order to increase the energy further, the Nb-film cavities were operated at up to 7.5 MV/m, well beyond their nominal field of 6 MV/m, which decreased somewhat their reliability because various faults triggered the interlock system resulting in about 2 h mean-time between trips which switched off a klystron and, therefore, 8 sc cavities. Since the rf system was operated such that 2 klystrons in stand-by feeding in total 16 cavities provided a voltage reserve of 160 MV, rf trips rarely resulted in beam loss. Although the Nb-film cavities were pushed hard, they turned out to be very robust, e.g. in 2000, only four cavities had to be completely detuned by the end of the run because they were damaged [\[32\]](#).

In order to reach the maximum possible beam energy in 2000, a number of measures were implemented: eight reserve copper cavities were added, the Nb-film cavities were conditioned at 7.5 MV/m before the run, reducing the rf frequency (by enhancing the energy damping the effective rf voltage was increased), using the dipole orbit correctors as additional bending magnets, and the operational strategy involved operating without any klystron reserve. The maximum useful energy was finally between 104.0 and 104.5 GeV [\[1\]](#). Had LEP been fully equipped with Nb-film cavities, the beam energy could have reached 111 GeV.

The calibration of the beam energy relied on the resonant depolarization method applied at lower energies, cross-calibrated with NMR measurements in dipoles, and NMR measurements at higher energy where the depolarization method could not be applied due to lack of polarization. The contribution of the beam uncertainty to the W mass determination was as low as 10 MeV/c² [\[34\]](#).

The maximizing of the performance at each energy required a continuous improvement and optimization of beam optics, beam observation, cryogenics, collimation for background-control, reliability of components, and interlock systems. In addition, operational procedures

had to be refined and adapted at the different energy steps. Even when in the year 2000 all systems and parameters were strained to a maximum, the down time of LEP was only 7.5% and an integrated luminosity of 233 pb^{-1} was obtained. The maximum luminosity of $1.0 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ was achieved in 1998 and 1999 with a total beam current of 6.2 mA and 4 bunches per beam. A token for the excellent performance of LEP 2 is the total integrated luminosity of 784 pb^{-1} per experiment accumulated at or above the W threshold [1].

4. Conclusions

The concept of LEP has been developed in a remarkable collaboration between experimental and theoretical physicists, accelerator physicists and engineers. Given that it has taken 6 years from first ideas to approval, a further eight years to the start of operations, and that LEP had been operated interleaved with gradual upgrading for eleven years, the team demonstrated a remarkable coherence paired with competence, great tenacity and perseverance. The vision of building an accelerator with a staged performance having the potential to eventually reach the W pair production threshold, turned out to be very fruitful.

LEP had at the end significantly surpassed all design expectations. It delivered over 200 pb^{-1} on the Z^0 resonance and almost 800 pb^{-1} at or above the W pair threshold. A number of new concepts were successfully applied and many technological challenges mastered together with European industry. The operation of LEP was stopped in November 2000 and LEP was dismantled [35] in the years 2001 and 2002 to clear the way for the LHC.

The maximum energy of LEP 2 was determined by the decision in 1996 to discontinue the industrial production of the superconducting cavities. Whether the potential of LEP should have been better fully exploited up to its reasonable limit of 220 GeV in the center-of-mass and whether this would have lead to the discovery of the Higgs particle as a number of models seemed to suggest [36, 37], is a matter of speculation. The quest for the Higgs particle will hopefully end with the results obtained by the Tevatron and the LHC. In any case, LEP will stand as a landmark in the development of particle accelerators.

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