THE LEP COLLIDER,
FROM DESIGN TO APPROVAL AND COMMISSIONING

Lecture delivered at CERN on 26 November 1990

Stephen Myers
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Abstract

A description is given of the design, approval, construction, and commissioning of the Large Electron–Positron storage ring (LEP) collider. The contribution of John Adams is highlighted both during his years as CERN's Director General and later as an active member of the LEP Machine Advisory Committee. The first injection into LEP took place in July 1989, first collisions for physics being about a month later. After one year of operation the LEP luminosity has reached more than half of the design value, and more than 900,000 $Z^0$ particles have been generated, detected, and analysed. The major factors relating to each significant improvement in performance are described. The present-day limitations to performance are analysed, and the foreseen improvements aimed at raising the performance are discussed. In addition, the time schedule and performance estimates for the planned upgrade in LEP energy to allow study of $W$ pair production are reported.
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1. THE CONTRIBUTION OF JOHN ADAMS TO THE DEVELOPMENT OF LEP

The early development of the Large Electron–Positron storage ring (LEP) project is best described by John Adams in his Annual Reports to the CERN Council in 1979 and 1980. I have extracted parts of these reports to highlight his enormous contribution to the early stages of the project.

"After many years of studies of different types of machines, ... the choice of the European community settled a year or so ago on a very large electron–positron collider called LEP.

"Studies of the design of the LEP machines started at CERN in 1976 and the first practical design was published in 1978. This machine had a cost-optimized energy of 70 GeV per beam and measured 22 km in circumference. After extensive discussions during the autumn of 1978 it was decided to embark on the design of a somewhat larger machine, 30 km in circumference, with a cost-optimized energy of about 90 GeV per beam. The energy of both these machines could be extended, by using superconducting RF cavities, when these become available, to 100 and 130 GeV respectively.

"Studies of the 30 km machine were completed during 1979 and a design report was issued in August. These studies ... cover not only machine design but also the design and development of the components of LEP machines. Progress on this part of the studies is most encouraging and already a much cheaper design for the main magnet system has been developed, and also a more economical system for the RF accelerating system using a storage cavity scheme. It was decided to increase the effort on the development of superconducting RF cavities for LEP by setting up a small team at CERN and establishing a collaboration with other European laboratories. ... The basic feature of the present LEP design is a large machine circumference in which the machine will be installed in stages corresponding to the new physics events that are predicted by the unified theory of weak and electromagnetic interactions. The first predicted event is the ... Z^0 at an energy of 90 GeV. Since these bosons can be produced singly, the LEP machine energy is about 50 GeV per beam, giving 100 GeV in the centre of mass. The next predicted event is the production of pairs of the charged intermediate boson — W^+W^- pairs — at an energy of about 180 GeV which requires LEP energies of about 90 GeV per beam.

"... To explore the Z^0 region, only a part of the RF accelerating cavities and their power amplifiers will be installed in the machine. To reach the next energy stage one has the choice either to install the full set of copper RF accelerating cavities or to install superconducting cavities, if they are ready at that time. ... All the other components of the LEP machine would be designed for the top energy envisaged but items such as power supplies would be installed for the energy stage being used at the time and extended only when the energy was increased. ..."

"... The latest development of the LEP Project is to use the PS and SPS machines as the injectors for LEP. ..."

2. THE LEP DESIGN

The two fundamental parameters in the design of any particle collider are the beam energy range and the luminosity. The energy must be sufficient to allow the observation of the required physics, and the luminosity must be sufficient to allow such observations at a reasonable rate. In the case of LEP the energy was clearly defined by that of the Z^0 and the W^± particles and resulted in a range of 40–100 GeV per beam. However, having decided
upon the energy, the next question in the design procedure is to optimize the physical size of the collider so as to minimize the capital and running costs. The crucial component in the definition of the circumference is the mechanism of synchrotron radiation. When the trajectories of charged particles are bent, as in the case of storage rings, to form a circular orbit, they radiate a fraction of their energy by emission of photons. If this energy were not replenished then the particles would rapidly decelerate in a spiral and finally be lost on the inside of the vacuum chamber wall. The radiation loss per revolution \( U_0 \) of a particle of energy \( E_b \) being bent in a circular path of radius \( \rho \) is given by

\[
U_0 = c_r \frac{E_b^4}{\rho} ,
\]

where

\[
c_r = \frac{4\pi}{3} \frac{r_e}{E_0^3} = 8.85 \times 10^{-5} \text{ m} \cdot \text{GeV}^{-3} ,
\]

with \( r_e \) being the classical electron radius = \( 2.8 \times 10^{-15} \) m and \( E_0 \) the rest energy of the electron = 0.511 MeV.

2.1 The beam energy

The RF acceleration system replenishes the energy lost by the particles on each revolution. Hence the power and cost of the RF system is defined, to a large extent, by the radiated power due to the synchrotron radiation. The power dissipated as heat in the accelerating resonant RF cavity wall is

\[
P_d = \frac{V_{RF}^2}{l r_{sh}} ,
\]

where \( V_{RF} \) is the peak accelerating RF voltage, \( l \) is the total active cavity length, and \( r_{sh} \) the shunt impedance per metre of the accelerating structure.

The RF voltage in the accelerating gaps oscillates at high frequency (352 MHz for LEP) and is synchronized to a harmonic \( (h) \) of the revolution frequency of the particles. Consequently, the bunches traverse the accelerating gaps at a constant phase \( \phi_b \) relative to the voltage. In this way all particles gain energy as they traverse the cavities. The energy gain per turn must compensate the energy loss per turn due to synchrotron radiation, i.e.

\[
U_0 = eV_{RF} \sin \phi_b .
\]

Combining Eqs. (1), (3), and (4) gives the power dissipation in the cavity walls as a function of the relevant beam parameters

\[
P_d = \left( \frac{c_r}{e} \right)^2 \frac{E_b^8}{l r_{sh} \sin^2 \phi_b \rho^2} .
\]

The power absorbed by the beams is

\[
P_b = 2k_b I_b \frac{U_0}{e} = 2k_b I_b c_r \frac{E_b^4}{e \rho} ,
\]

where \( I_b \) is the current per bunch and \( k_b \) the number of bunches per beam.

The total power needed then is simply

\[
P_{tot} = P_d + P_b .
\]
For the case of room-temperature accelerating cavities, the power dissipated in the cavity walls is predominant and scales with the *eighth* power. For a given beam energy, this power may be minimized by optimizing:

i) the total active length of the cavities, \( l \);

ii) the shunt impedance per metre of each cavity, \( r_{sh} \);

iii) the 'overvoltage factor', \( \sin \phi_s \);

iv) the bending radius of the bending magnets, \( \rho \).

### 2.1.1 Active length of cavities

Clearly, from Eq. (5), increasing the active cavity length will reduce in proportion the power dissipated in the cavity walls. As well as the increased costs due to the increase of the number of cavities, this approach has two other undesirable consequences:

i) The RF straight sections which house the cavities will also need to be extended. This would necessitate an increase in the circumference of the tunnel as well as of all the associated costs for civil engineering, additional quadrupole magnets, vacuum chamber, etc.

ii) The total impedance seen by the beam increases linearly with the number of cavities. This impedance can limit the performance of the collider, as described later.

### 2.1.2 Shunt impedance

The effective shunt impedance of resonant cavities can be increased by optimization of the geometry of the cavities themselves. In particular, the beam port-hole radius has a strong influence on the shunt impedance. For the design of the LEP accelerating cavities, large electromagnetic computer codes were used to maximize the shunt impedance. However, once again, there is a possible pitfall; reduction of the beam port-hole radius not only increases the shunt impedance but also increases the transverse impedance. In fact, the transverse impedance increases with approximately the third power of this parameter. For this reason, the beam port-hole radius in the accelerating cavities was not pushed to the aperture limit for the LEP beams. The effective shunt impedance in LEP was also increased by the addition of a low-loss 'storage cavity' coupled to the accelerating cavity (see later). This technique increases the effective shunt impedance by \( \sim 60\% \).

### 2.1.3 The overvoltage factor

The overvoltage factor is simply the ratio between the peak RF voltage and the voltage loss per turn of the particles due to synchrotron radiation, and from Eq. (4) is simply \((\sin \phi_s)^{-1}\). As each particle circulates in LEP it performs oscillations in energy and azimuthal position with respect to a perfect 'synchronous' particle. The maximum possible amplitude of these oscillations is usually referred to as the 'RF bucket'. The maximum energy oscillation defines the full half-height of the RF bucket and is given by

\[
\left( \frac{\Delta E}{E} \right)_{\text{buck}} \approx Q_h \sqrt{\frac{eV_{\text{RF}}}{hE_b} \left( \frac{2}{\pi} \cos \phi_s - \left( 1 - \frac{2\phi_s}{\pi} \right) \sin \phi_s \right)},
\]

where \( Q_h \) is approximately the number of horizontal betatron oscillations per revolution and is indicative of the strength of horizontal focusing.

In addition to this synchronous motion, the particle is subjected to random energy losses at random times along its trajectory. These losses result in a 'heating' effect, whereas
since the average loss per turn depends on the energy offset from the synchronous particle, a damping of the energy oscillation results. The energy damping time is given by

$$\tau_e = \frac{E_b}{U_0 f_{rev}},$$

(9)

where \( f_{rev} \) is the revolution frequency of the particles.

Consequently, the motion of each particle in the energy phase plane is a series of random jumps followed by damping. Averaging this type of motion over a very large number of particles results in an equilibrium energy distribution of the particle ensemble. Although individual particles are continuously interchanging positions within this distribution, the distribution itself is constant in time and Gaussian in form. Solving the equations of this type of motion gives the r.m.s. energy spread of the beam, i.e.

$$\frac{\sigma_E}{E} = \gamma \sqrt{\frac{c_q}{2\rho}},$$

(10)

where \( \gamma \) is the relativistic energy \( E_b/E_0 \), and

$$c_q = \frac{55hc}{64\pi\sqrt{3}E_0},$$

(11)

where \( h \) is Planck's constant and \( c \) the speed of light. Note that \( c_q \) is very close to the Compton wavelength of the electron.

When the energy acceptance of the RF bucket is not much larger than the energy spread of the particle distribution, there is a non-zero probability that the energy fluctuations of some particles may cause them to 'jump' outside the stable region. In practice, this will result in those particles continuously losing energy until they are finally lost against the inner vacuum-chamber wall. The half-life due to this effect, usually referred to as the quantum lifetime, is given by

$$\tau_q = \tau_e \left( \frac{\sigma_e}{E} \right)^2 \exp \left( \frac{\Delta E^2}{2\sigma_e^2} \right).$$

(12)

Consequently, a possible simplified procedure for calculating the required RF voltage and resulting stable phase angle is as follows:

i) For a given energy, Eqs. (1), (10), and (9) are used to evaluate \( U_0, \sigma_e/E \), and \( \tau_e \).

ii) For the specified quantum lifetime, Eq. (12) gives the required energy acceptance of the RF bucket.

iii) Finally, the solution of Eqs. (4) and (8) gives the necessary values of \( V_{RF} \) and \( \phi_a \).

Clearly, from Eq. (8), for a given RF voltage the energy spread of the bucket is proportional to \((\sqrt{h})^{-1}\). Hence in order to minimize the overvoltage factor one should operate at the minimum possible RF frequency \((f_{RF} = hf_{rev})\) and the maximum horizontal tune value \((Q_h)\), i.e. the strongest possible focusing. However, reducing the frequency of the accelerating structure is severely constrained for two main reasons. Firstly the physical size of the structures increases, as do concomitant costs. Secondly, high-power RF sources (such as klystrons) are uneconomical at frequencies below \( \sim 300 \) MHz. For these reasons the frequency of the accelerating structure was chosen to be 352 MHz, which corresponds to 31,320 times the revolution frequency. The second variable parameter in Eq. (8) is the horizontal betatron-tune value. From the point of view of minimizing the overvoltage factor, it is clear that very strong focusing (i.e. high \( Q_h \)) is to be preferred. However, it will be seen later that there are other constraints on this parameter.
2.1.4 The bending radius of the dipole magnets

From Eqs. (5) and (6), it is clear that the bending radius $\rho$ is the most critical parameter in the minimization of the RF power for a given energy. In the early design stage of the LEP collider it was considered essential that the maximum energy needed for $W$-pair production could be reached by the use of conventional room-temperature accelerating cavities and not be totally dependent on the future development of superconducting structures. Nevertheless, a huge effort was put into such development since it was known that great savings could result from the improvement in operational efficiency of the collider. At the time, an upper limit on the amount of high-frequency power was considered to be around 100 MW. This upper limit combined with the then-known cavity gradients and shunt impedances gave, using Eq. (5), a bending radius of $\sim 3.5$ km. This value and the length of the straight sections of more than 2 km in length needed to house the 768 cavities brought the circumference of LEP to 27 km. It may now be said that this optimum value for the bending radius would have been slightly less ($\sim 10\%$) if it had been optimized for superconducting cavities using Eq. (6). However, this contingency is already being used up by requests to go to energies beyond those previously foreseen, both for $e^\pm$ and protons.

For phase 1 of LEP, the energy needed was only around 50 GeV per beam, and required much less power, in fact only 16 MW. Consequently, it was decided for this initial phase to buy and install only one sixth of the foreseen room-temperature cavities and continue with the development of superconducting cavities. In this way, both options were left open for the second phase. The present scheme for increasing the beam energy to around 90 GeV requires the installation of 192 superconducting cavities with an additional required power of only 12 MW (see Section 6.1).

2.2 The luminosity

The second important performance parameter in the design of colliding-beam rings is the luminosity ($\mathcal{L}$). For any physical process (such as, for example, production of the $Z^0$), the rate at which the events are produced is given by

$$\frac{dN}{dt} = \sigma \mathcal{L},$$

where $\sigma$ is the cross-section of the process.

For beams colliding ‘head-on’, the luminosity at any collision point is given by

$$\mathcal{L} = \frac{N_eN_p k_b f_{\text{rev}}}{4\pi \sigma^*_x \sigma^*_y},$$

where $N_e$ and $N_p$ are the number of electrons and positrons per bunch, respectively, and $\sigma^*_x \sigma^*_y$ is the cross-section of the bunches at the collision point.

A fundamental limitation to all electron–positron colliders results from the influence of the electromagnetic field associated with each beam, on the motion of the particles in the ‘other’ beam. This ‘beam–beam effect’ is quantified by the beam–beam strength parameter ($\xi$) and is often loosely referred to as the beam–beam tune shift:

$$\xi_y = \frac{\beta^*_y}{4\pi} \frac{\Delta y'}{y_0},$$

where $\Delta y'$ is the angular deflection [$\Delta(dy/ds)$] given to a particle at a vanishing displacement from the centre of the other beam, $y_0$; $s$ is the longitudinal coordinate, and $\beta^*_y$
is the betatron amplitude function at the location of the beam–beam interaction, which specifies the strength of focusing at that point.

Evaluation of the deflection \( \Delta y' \) requires calculation of the electrical potential of the beam’s three-dimensional Gaussian charge distribution. For small displacements, and for \( \sigma_x^* \gg \sigma_y^* \), Eq. (15) becomes

\[
\xi_y = \frac{N_b r_e}{2\pi \gamma} \frac{\beta_y^*}{\sigma_x^* \sigma_y^*}.
\]

Combining Eqs. (14) and (16), and assuming that the bunches in both beams have the same number of particles \( (N_b) \), the luminosity is obtained in a more useful form, i.e.

\[
\mathcal{L} = \frac{\gamma f_{rev} k_b}{2 r_e} \frac{N_b \xi_y}{\beta_y^*}.
\]

Since the beam energy and the revolution frequency in Eq. (17) have already been discussed in the previous sections, the independent parameters to be varied in order to optimize the luminosity are

i) the number of particles per bunch \( (N_b) \),
ii) the number of bunches \( (k_b) \),
iii) the vertical beam–beam strength parameter \( (\xi_y) \),
iv) the betatron amplitude function at the collision points \( (\beta_y^*) \).

2.2.1 The number of particles per bunch

In LEP the intensity per bunch is limited by two main beam instabilities:

i) the transverse-mode coupling instability (TMCI) or the fast head–tail instability;
ii) synchro-betatron resonances.

The TMCI is caused by the interaction of the particles in the bunch with their own short-term transverse wake field. As particles at the front of the bunch circulate in the vacuum chamber they generate, via their own electromagnetic field, high-frequency waves in cavity-like components surrounding the beam trajectory. These high-frequency waves are often referred to as wake fields; or the ‘impedance’ of the component is defined as the voltage generated in it divided by the electric current of the bunch. The strength of the transverse wake field is given by the product of the impedance of the component, the beam intensity, and the distance off-axis of the generating particles. These wake fields then excite those particles which are behind, causing an increase in their transverse oscillation amplitude. However, since particles oscillate around the synchronous particle both in energy and in longitudinal position, the particles at the rear of the bunch, having been excited to larger transverse amplitudes, soon find themselves at the head of the bunch and can now generate even larger wake fields owing to their increased transverse oscillation amplitude. It may be apparent that this situation can lead to an ever-increasing growth in the oscillation amplitude of the bunch. This unstable growth ultimately drives the particles against the vacuum-chamber wall.

The approximate threshold for the onset of this instability is given by

\[
N_{th} = 8 \left( \frac{f_s}{f_{rev}} \right) \frac{E_b}{e^2 \sum \beta_i k_{\perp i} (\sigma_e)}
\]

where \( f_s \) is the frequency of the energy oscillation, \( \beta_i \) is the betatron amplitude function at the location of the impedance, and \( k_{\perp i} (\sigma_e) \) is the transverse loss factor of the impedance seen by the beam and increases with the length of the bunch \( \sigma_e \).
Clearly, in order to maximize the intensity at which this instability occurs, it is necessary to minimize the impedance seen by the beam. In principle, this would simply require a completely smooth vacuum chamber, without any cross-section changes. In practice, however, there are many accelerator components which require these changes in order to perform their function; for example, the RF cavities, the bellows which join up long lengths of vacuum chamber, the electrostatic plates, etc. For this reason, substantial effort went into the design of all components seen by the beam in order to minimize their impedance. In addition, the magnetic optics of the machine were modified at locations of large impedance (such as the RF cavities) so as to minimize the \( \beta \) there. The impedance of all components was also either measured or computed before authorization was given for installation in the tunnel. In particular, the vacuum bellows, of which there are 2800 in total, are of a completely new design so as to minimize their transverse impedance.

During the first few months of operation the LEP impedance was measured using the beam and found to be slightly less than had been estimated; LEP has the lowest impedance of any accelerator ever built.

2.2.2 The number of bunches

From Eq. (17), the luminosity may be increased in direct proportion to the number of bunches. For a collider with \( n \) experimental collision points, the minimum number of bunches required to illuminate all experiments is \( n/2 \). There are several consequences associated with increasing the number of bunches beyond this minimum value:

i) The beam–beam effect

It is undesirable to allow the bunches to interact in the unwanted collision points for two main reasons. Firstly the maximum beam–beam tune-shift parameter is reduced by the increased number of ‘kicks’ per turn, and secondly the lifetime of the beam intensity is reduced owing to the increased number of \( e^+e^- \) collisions. The beams may be separated in the unwanted collision points by the use of electrostatic plates. The electric field in the gap of such plates deflects the electrons in one direction and the positrons in the other, thereby causing the bunches to pass each other with a vertical displacement. In LEP there are four bunches and four experimental collision points; consequently each of the four unwanted collision points are equipped with a set of four electrostatic separators (see Section 3.5).

ii) Beam power

Increasing the number of bunches of course increases the total beam current and hence the beam power [see Eq. (6)]. The beam power for LEP phase 1 is only 1.2 MW; however for phase 2 the beam power is \( \sim 12 \) MW for the design current of 3 mA per beam. Consequently, increasing the number of bunches by, say, a factor of ten would necessitate a beam power of 120 MW for phase 2.

iii) Coupled-bunch instabilities

Long-term wake fields couple the motion between bunches in much the same way as short-term wake fields couple the head to the tail. The strength of this coupling is directly related to the spacing between the bunches. At present, in LEP with four bunches per beam there is a longitudinal coupled-bunch instability which has necessitated a beam feedback system. The cost and complexity of such feedback systems increases with the required bandwidth and power. Both these parameters increase with the number of bunches.
iv) Detector considerations

The electronics in experimental detectors have finite times available for particle identification and triggering sequences. The complexity and cost of these electronics increase as the time between successive collisions decreases (or the number of bunches increases).

For these reasons, the design of LEP phase 1 was for four bunches per beam with a system of electrostatic plates separating the beam in the four unwanted collision points. However, when more power becomes available for LEP phase 2 it may be possible, at the lower energies of, say, the $Z^0$, to increase the number of bunches substantially and thereby provide increased luminosity at lower energies. This option is at present being studied and will be described in Section 6.2.

2.2.3 The beam–beam strength parameter

Associated with each bunch is a strong, very non-linear electromagnetic field which deflects individual particles of the counter-rotating beam at each collision. For small displacements from the centre of the bunch this field varies linearly with displacement, similarly to a normal quadrupolar magnetic lens, whereas at larger displacements the field is highly non-linear. It is these non-linear fields which do the damage. However, since the magnitude of the non-linear components is directly proportional to the linear term, the strength of the beam–beam force is usually quantified by this linear term, called the beam–beam strength parameter, and is given by Eq. (16). In previous accelerators the maximum 'beam–beam limit' ever measured was at values of $\sim 0.06$ for this strength parameter.

From Eq. (17) it is apparent that the maximum luminosity is achieved when the beam–beam strength parameter ($\xi_y$) is at a maximum simultaneously with the beam intensity. To this end, Eq. (16) may be written as

$$\xi_y = \frac{N_b r_e}{2 \pi \gamma \epsilon_x},$$

where $\epsilon_x$ is the horizontal emittance, and can be approximated by

$$\epsilon_x = \frac{\sigma_x^2}{\beta_x} = \frac{c_e R}{\rho \gamma^3},$$

$R$ being the average radius of the orbit.

Combining Eqs. (19) and (20) gives

$$\xi_y = \frac{N_b r_e \rho Q_h^3}{2 \pi c_e R \gamma^3}.$$  \hspace{1cm} (21)

Consequently, for a given energy, Eq. (21) shows that, if the intensity is too low to reach the beam–beam limit, increasing the focusing will reduce the emittance and allow higher values of $\xi$. It is also evident that as the beam energy is increased the beam–beam strength parameter decreases with the third power. For LEP two focusing optics have been foreseen; a low-energy optics with a phase advance per cell of 60° and a high-energy optics of 90° per cell. However, for intensities lower than the design value, the 90° per cell optics could be used to increase the $\xi$ parameter and thus the luminosity.

Since the beam–beam strength parameter varies inversely with the third power of beam energy, then if the beam–beam limit is to be attained at the maximum energy,
it will be greatly exceeded at injection energy. For example, in LEP at injection energy the beam–beam strength parameter would be $\sim 1.25$ if the beams were to collide with the design currents. This, of course, would be an impossible condition and the bunches would literally explode and be lost against the vacuum-chamber wall. This is avoided by separating the beams at the collision points by electrostatic plates. Experiments done at injection energy in LEP have shown that the current per bunch is limited to $\sim 0.03$ mA (compared with a design value of 0.75) if the bunches are not separated in the collision points.

2.2.4 The betatron amplitude function at the collision point

The final parameter to be optimized in Eq. (17) is the betatron amplitude at each collision point ($\beta_y^*$). This parameter can be reduced by very-strong local focusing at these points. This is accomplished by a set of superconducting quadrupoles around each experiment, which causes a reduction in the beam cross-section ($\sigma_x^*\sigma_y^*$) and hence an increase in the density of collisions. The minimum value for $\beta_y^*$ is limited by the chromatic aberrations introduced by these 'low-$\beta$ quadrupoles'. In short, since the focusing strength is inversely proportional to the particle energy then the energy spread of the beam produces a spread in the focusing or a 'tune spread'. This natural chromaticity is corrected by a set of sextupoles, which are arranged in the lattice so that they produce a controllable tune dependence on energy. However, the sextupoles themselves generate higher-order effects, such as tune dependence on betatron amplitude, which limit the amount of sextupoles and thereby the allowable chromatic aberration due to the low-$\beta$ quadrupoles.

3. CIVIL ENGINEERING AND ACCELERATOR COMPONENTS

3.1 Civil engineering

Chronologically the LEP construction began with the civil-engineering work and the infrastructure. This work accounted for more than half of the total LEP construction budget, and between 1983 and 1988 LEP was the largest civil-engineering undertaking in Europe. The 26.67 km Main Ring tunnel formed the most impressive part of this work, even though it represented less than half of the $1.4 \times 10^6$ m$^3$ of material which had to be excavated for the project. The remainder of the underground work consisted of the four experimental caverns, 18 pits, 3 km of secondary tunnel, and some 60 chambers and alcoves (see Fig. 1). After an extensive campaign of test borings in and around the area proposed for the LEP tunnel it was decided to incline the plane of the tunnel by 1.4% (see Fig. 2). This decision was made so as to ensure that all underground caverns and the main part of the tunnel would be located in solid rock while, at the same time, limiting the maximum depth of the shafts to less than 150 m. However, owing to the necessarily large diameter of LEP and the constraining distance between Geneva airport and the foothills of the nearby Jura mountains, it was inevitable that some part of the tunnel had to be bored under unfavourable conditions created by the limestone. This part, which consisted of around 3.5 km, was excavated by blasting, and the poor quality of the rock necessitated an increase in the thickness of the roof lining to 40 cm. As anticipated, many geological faults had to be traversed here but most were detected in advance by systematically boring pilot holes ahead of the excavation. Nevertheless, in spite of all the care taken, several major inundations of water ($150$ l/s at $13 \times 10^5$ Pa pressure was recorded) and clay occurred, and delayed the work by several months. Excavation of the part of the
Fig. 1 Experimental cavern

Fig. 2 Inclined plane of the tunnel
tunnel in the rock ($\sim 23$ km) progressed at a much faster rate, owing to the use of three full-face tunnelling machines, each of which progressed at an average rate of $\sim 25$ m per day.

The guidance of the tunnelling machines on their desired trajectory to a precision of $\sim 1$ cm and the alignment of the collider components within the LEP tunnel to a required short-range relative precision of less than $\sim 0.1$ mm on the scale of many kilometres is worthy of note. The basic reference for this work was provided by a geodesic network between the hills surrounding the site. The base lines of up to 13 km length were measured with precisions of $10^{-7}$ by the use of a two-wavelength laser interferometer (Terrameter). Recently these measurements have been verified with excellent agreement by satellite observations using the NAVSAT satellite system. The first precise measurements with beams indicated that the LEP circumference was in fact more than twice as precise as predicted; better than 1 cm in 26.67 km.

In addition to the underground civil-engineering work, the construction of LEP necessitated the construction of 71 surface buildings of a total area of some 51,000 m², situated over eight sites. This was done in a way which preserved the local environment.

The LEP infrastructure, although often industrial in nature, presented a great challenge owing to its enormous size and the very tight time and budget constraints. This infrastructure consisted of the many types of water cooling, air conditioning and treatment, and the electrical distribution scheme as well as the transport and installation schemes.

3.2 Magnet and power-converter systems

The electromagnetic guide field system of LEP consists of dipoles, quadrupoles, sextupoles, horizontal and vertical dipole correctors, rotated quadrupoles, and finally electrostatic dipole deflectors. About three quarters of the LEP circumference is occupied by 'standard cells'. Each of the eight arcs contains 31 of these standard cells, which are comprised of magnets in the following order: a defocusing quadrupole, a vertical orbit corrector, a group of six bending dipoles, a focusing sextupole, a focusing quadrupole, a horizontal orbit corrector, a second group of six bending dipoles, and finally a defocusing sextupole (see Fig. 3). The length of a standard cell is 79.11 m. The electrons and positrons are bent in a piecewise circular trajectory by the strings of dipole magnets. As previously indicated, the bending field of these dipoles has been made unusually low ($\sim 0.1$ T) so as to increase the bending radius and thereby reduce the amount of synchrotron radiation. The low bending field allowed a novel design of the dipole magnet cores, with the 4 mm gaps between the steel laminations (1.5 mm thick) filled by mortar. Compared with classical steel cores, this produced a cost saving of around 40%. The quadrupole magnets, which produce fields linear with the transverse position, act as magnetic lenses and focus the beam to be comfortably contained within the vacuum chamber. The alternating polarity of the quadrupoles in the standard cells produces alternating-gradient focusing or 'strong' focusing. The cell sextupoles produce a field which is quadratic in transverse displacement, and they are used to compensate the dependence of the focusing strength on the beam energy ('chromaticity'). The small horizontal and vertical correctors are individually powered so as to allow 'steering' of the beam through the centre of the LEP aperture.

Each experimental collision point in LEP is surrounded by a large solenoidal magnet used for particle identification. The bunches of each beam must be tightly focused ('squeezed') to very small dimensions in the centre of these detectors in order to increase
the luminosity or particle production rate. This is accomplished by a set of superconducting quadrupoles with very strong field gradients that focus the transverse beam dimensions to $\sim 10 \, \mu m$ and $250 \, \mu m$ in the vertical and horizontal planes respectively. The solenoidal detector magnets produce another effect, however: they cause the horizontal oscillations to be 'coupled' into the vertical plane; if this were uncompensated it would greatly increase the vertical beam size and cause a reduction in the luminosity. For this reason, rotated quadrupoles are installed around each solenoid to compensate this magnetic coupling. These quadrupoles are similar to conventional quadrupoles but rotated about their axis by $45^\circ$.

The strengths of all magnets in the LEP ring are very accurately adjusted by controlling the current flowing in their coils. This is accomplished by the use of more than 750 precisely stabilized d.c. power supplies ranging from less than 1 kW to a maximum of 7 MW. The specifications for these power supplies are extremely tight, both in their individual operation and, during energy ramping, in their precise synchronization. For the main dipole and quadrupole supplies, absolute accuracies down to 2 parts in $10^5$ have been achieved with a resolution typically three times better.

Each magnet has, of course, its own cooling circuit. For the majority, the cooling is provided by demineralized water circuits, which are connected to a total of 10 cooling towers with a capacity of 10 MW each. Some of the small corrector magnets are air-cooled, whilst the superconducting quadrupoles and the superconducting experimental solenoids are cooled by liquid helium at 4.2 K from the cryogenics installation.
3.3 Acceleration system

The RF acceleration system installed at present consists of 128 five-cell copper cavities powered by sixteen 1 MW klystrons via a complex of waveguides and circulators. Each accelerating cavity is coupled to a spherical low-loss storage cavity in such a way that the electromagnetic power continuously oscillates between the two sets of cavities (see Fig. 4). The coupling is arranged so that the power is at its peak in the acceleration cavities at the instant of the passage of the beam bunches. In this way, the bunches receive the maximum possible accelerating gradient, but the power loss due to heating of the copper cavity walls is greatly reduced since the electromagnetic power spends half of its time in the very-low-loss storage cavities. The operating frequency is 352.21 MHz, which corresponds to 31,320 times the revolution frequency of a beam circulating in LEP. The present system allows for a peak RF voltage of 400 MV per revolution.

The sinusoidal electric field that is generated in each accelerating cavity cell produces a 'potential well', inside which each particle of each bunch can perform stable oscillations with respect to the particle at the centre of the bunch, i.e. the synchronous particle. These oscillations are around the energy of the synchronous particle and, in azimuthal distance, ahead of or behind this particle. When represented in a phase-plane plot of normalized energy as a function of normalized distance, the trajectories form circles for the case of small oscillation amplitudes while the maximum stable oscillation possible inside the potential well forms a closed contour which, in accelerator jargon, is called an RF bucket. It may now be appreciated that there can possibly be as many synchronous particles and hence stable regions (buckets) as there are RF oscillations in the revolution.

Fig. 4 Accelerating and storage cavities
time of LEP. As previously stated, this means a total of 31,320 buckets for LEP, with the possibility of stable oscillations in each. However, in order that the $e^+e^-$ bunches collide at the centres of the experimental detectors, they must be injected and accumulated in precisely the correct buckets. This is achieved by a very precise synchronization system between the RF systems of LEP and its injector, the SPS.

Since each particle performs an oscillation about the synchronous particle, it receives, on an average over many turns, a net energy gain per turn equal to that of the synchronous particle. This (and therefore all other particles) receives an energy gain per turn of $V\sin \phi_s$. Owing to the previously mentioned synchrotron damping, the beam will perform a damped phase oscillation to the exact $\phi_s$ needed to make the energy gain per turn equal to the energy loss per turn. Consequently, the RF acceleration performs two main functions. Firstly, it replenishes the energy lost by the beam because of synchrotron radiation, and, secondly, it focuses the particles longitudinally and in energy into discrete bunches. In LEP the bunch length is typically 1–2 cm and the relative energy spread typically 0.1%.

3.4 Beam instrumentation

The LEP beam-instrumentation system is used to observe the position, shape, or other relevant properties (such as polarization or electrical current) of the beam. There are two ways of ‘observing’ the beam. The first and most simple is by placing a monitor directly in the path of the primary beam: an example of this is the luminescent screen that is used to observe the position and shape of the injected beam. The beam particles interact with the chromium in the screen and produce a luminescent image of the cross-section of the beam which is transmitted as a television signal to the control room. These monitors are very useful in the early days of commissioning when the other, more sophisticated monitors are perhaps not yet fully tested, and in the case of LEP they were used to steer the beam through the first turn. The beam electrical current is measured in LEP as in other accelerators by current transformers placed around the vacuum chamber. These transformers are capable of measuring the current of a single injection or of a steady circulating beam. In the latter case the beam lifetime can be evaluated by accurate measurement of the current as a function of time.

In order to position the beam accurately in the middle of the vacuum aperture, it is essential to measure the transverse beam positions at many azimuthal locations on the circumference. In the case of LEP this ‘closed orbit’ is measured by 504 monitors fairly evenly distributed around the circumference. Each monitor forms part of the vacuum chamber and consists of four electrostatic pick-up ‘buttons’; these are positioned in housings which, for alignment and accuracy reasons, are connected directly to the end faces of the quadrupole magnets. The electromagnetic field of the bunches induces voltages on each of the four buttons; when properly analysed, these can give an accurate measurement of the horizontal and vertical beam positions relative to the centre of the monitor. This system has been designed to be capable of measuring the positions of all eight individual bunches during more than 1,000 revolutions to an accuracy of better than a millimetre.

The betatron-tune value is defined as the number of transverse oscillations, around the closed orbit, made by the beam per revolution. The measurement and correction of this parameter is of paramount importance for the stability of a beam in a storage ring. Owing to non-linear resonances driven by magnetic imperfections in the guide field, there are many undesirable values for the horizontal and vertical betatron tunes as well as
undesirable combinations of the two. In LEP the betatron-tune values (or the $Q$ values) are measured by two $Q$ meters, one for each plane. The $Q$-meter system consists of a magnetic beam 'shaker', which excites the beam, and of dedicated electrostatic pick-ups, which measure the phase and amplitude of the induced transverse oscillations as a function of the excitation frequency. Since the beam acts as a high-quality resonator, the amplitude of the response is at a maximum when the excitation frequency equals the natural resonant frequency of the beam; this gives the betatron-tune value. In addition, the excitation can be 'phase-lock looped' to the beam response (acting in the same way as a modern FM receiver), thereby giving a continuous readout of the betatron-tune values. This mode of operation is particularly beneficial during energy ramping, where the tune values may wander. A system is now operational which continuously maintains the tune values at their previously prescribed values by automatically adjusting the excitation of the focusing system.

As previously described, when charged particles are bent in a circular trajectory they radiate photons. Consequently, the beams can be 'seen' by measuring this flux in the ultraviolet (UV) frequency range (see Fig. 5). Four UV monitors are used in LEP to measure the transverse dimensions of both beams at two different locations. The UV range is preferred because it produces a sharper image on the digital TV camera. The images are transmitted to the control room to give a real-time view of the beam, while the digital signals are processed to provide numerical values for the beam sizes (see Fig. 6). The UV synchrotron radiation monitors cannot give the absolute beam dimensions; they are therefore calibrated using the 'wire scanner monitor': a 37 $\mu$m diameter carbon fibre traverses the beam at 0.5 m/s and thereby creates photons which are detected outside the vacuum chamber. The beam profile is given by the density of the detected photons, plotted as a function of the position of the flying wire, which can be measured to an accuracy of 10 $\mu$m. The synchrotron light signal can also be used to measure the length of the bunch with picosecond precision.

![Diagram of UV synchrotron light monitor](image-url)

**Fig. 5** Schematic view of the UV synchrotron light monitor
Fig. 6 Computerized display of the beam cross-section from the UV monitor

The synchrotron radiation results in another problem: background originating from the high-energy spectrum of the photon emissions. In order to reduce this background, collimators are installed around each experimental point. Each of these collimators consists of remotely movable jaws of tungsten and copper, which can intercept and absorb the high-energy photons. Since these collimators can be placed very close to the beam, they were designed to accommodate, inside each horizontal jaw, a mini-calorimeter consisting of tungsten absorbers and silicon detectors. These mini-calorimeters are used to measure the relative luminosity in each experimental point by counting the number of Bhabha events at very small angles to the beam trajectory. In addition, other collimators are located far from all the experiments: these define the LEP aperture and remove any beam halo that might otherwise end up in one of the detectors. The system of collimators has proved invaluable in LEP and has resulted in low background conditions in the detectors practically from the first physics run.

3.5 Electrostatic separators

As described previously, under certain circumstances it is essential that the beams of electrons and positrons do not collide. This is particularly true at injection energy, where the electromagnetic fields associated with each bunch would destroy the opposing bunch long before a sufficient number of particles could be accumulated. If electrons and positrons, travelling in opposite directions, are subjected to the same transverse
electrostatic field, they will be displaced in opposite directions, thereby avoiding collisions and greatly reducing the beam–beam effect. In LEP this has been achieved by equipping each of the eight possible collision points (four bunches could make eight collision points) with four electrostatic separators, each of which is 4 m long and produces a vertical electric field of 2.5 MV/m between the plates, which are separated by 11 cm. This produces a separation between the bunches of electrons and positrons of more than 40 standard deviations of the vertical beam size ($\sigma_y$). The separators are powered in all eight possible collision points during injection, accumulation, and energy ramping. Some time before physics data taking starts the separators in the experimental points are switched off to allow collisions. At higher energies in LEP however, the bunches may not necessarily collide perfectly ‘head-on’, even if the separators are off. For this reason the separators have been equipped with a vernier adjustment, which allows vertical steering of the beam positions in the collision points down to a precision of $\sim 0.1\sigma_y$. The LEP separators have been designed to have a very low ‘spark-over’ rate: less than one spark per 1000 hours of operation even in the presence of synchrotron radiation. In addition, owing to their proximity to the experimental detectors, they must be compatible with the ultrahigh-vacuum requirements imposed by the low-background conditions needed in the collision areas.

3.6 Vacuum system

The duration of a typical operation to fill LEP with particles for a physics run is 12 h. During this time each of the $10^{12}$ particles in the beams will have traversed the complete 26.67 km of the LEP vacuum chamber about 500 million times. In order to minimize particle losses due to collisions with residual gas molecules, the whole vacuum chamber must be pumped down to very low pressures. The achieved static pressure for LEP is $8 \times 10^{-12}$ Torr, whereas in the presence of beam the pressure rises to $\sim 10^{-9}$ Torr. This pressure rise is due to gas desorption from the inner vacuum-chamber wall, provoked by the synchrotron radiation of the circulating beam, and has had a profound influence on the design of the LEP vacuum system.

The two main components of the vacuum system are the vacuum chamber itself and the pumping system. Of the 27 km of LEP vacuum chamber, a length of about 22 km passes through the dipole and quadrupole magnets, and is subjected to the heating due to synchrotron radiation. Although this heating represents a mere 100 W/m for phase 1, it rises to more than 2000 W/m for phase 2. Therefore the chambers need water-cooling channels and are constructed from aluminium because of its good thermal conductivity. However, only about half the radiated power would be absorbed by the aluminium; the remainder would normally escape into the tunnel and produce such a high radiation dose that organic materials such as gaskets, cables, electronic components, etc., would be rapidly destroyed. In addition, severe damage could result from the formation of ozone and nitric oxides, which produce highly corrosive nitric acid in the presence of humid air. For these reasons, the aluminium chamber is covered with a lead cladding of a thickness varying between 3 and 8 mm, which greatly reduces the radiation that escapes into the tunnel during operation (see Fig. 7). These chambers are interconnected by bolted flanges with aluminium gaskets and stainless-steel bellows, which allow for minor misalignments during installation and thermal expansion during machine operation and high-temperature ‘baking’ of the chambers. Other types of chambers are used in special regions such as the injection, RF, electrostatic separators, and the detector regions. For
the main part these are made of stainless steel except for the detector regions where, for reasons of transparency to particles, they are fabricated from beryllium, thin-walled aluminium, or carbon-fibre composites.

For reasons of reliability the 26.7 km of the LEP vacuum system is subdivided into smaller ‘vacuum sectors’ with a maximum length of 474 m. During shutdown periods, when there is no circulating beam and work is often going on in the tunnel, these vacuum sectors are isolated from each other by full-aperture gate vacuum ‘sector valves’. Consequently, if an accident occurs, only 474 m of vacuum will be affected and not the full 26.7 km.

There are two independent pumping systems for each of these sectors: a rough system, which provides pressures down to the $10^{-4}$–$10^{-5}$ Torr range; and the second system needed to provide and maintain ultrahigh vacuum. In previous electron storage rings, the ultrahigh vacuum was normally produced by linear sputter-ion pumps operating in the field of the bending magnets. However, this proved impossible in LEP since the bending-field strength is below the threshold for efficient operation of such pumps. Consequently, a novel type of ultrahigh-vacuum pumping system was required for the LEP storage ring.

The solution adopted, for the first time in an accelerator, was the use of non-evaporable getter (NEG) strips, installed in pumping channels running parallel to the beam channel with pumping holes between the two (see Fig. 7). The NEG strip is 3 cm wide, and extends over 22 km. It is fabricated by coating constantan with a zirconium–aluminium alloy. The NEG material forms stable chemical compounds with the majority of the active gases; consequently the residual gas molecules inside the pumping channel simply ‘stick’ to the NEG ribbon. During long periods of pumping, the getter surface becomes progressively saturated and loses some of its pumping capacity. An essential operation is therefore reconditioning; this consists of heating the getter up to 400°C for about 15 min and results in the diffusion of O₂ and N₂ from the saturated surface layer into the bulk of the material.
The very low static pressure of less than $10^{-11}$ Torr requires initially very clean internal surfaces. This was achieved by careful chemical cleaning of all chambers, followed by storage under chemically inert conditions. After installation in the tunnel all chambers were 'baked out' at 150°C for 24 h. The bakeouts were performed by pumping superheated water at 150°C and at a pressure of $5 \times 10^5$ Pa into the cooling channels of the aluminium–lead chambers. Sputter-ion pumps, valves, gauges, all stainless-steel chambers, and special equipment such as the electrostatic separators and the feedback system, were baked out by electrical heating elements and jackets.

### 3.7 Controls system

Almost every single LEP component and piece of equipment must be remotely controllable from the main control room by means of the LEP computer control system, which consists of more than 160 computers and microprocessors distributed over 24 underground areas and 24 surface buildings. Communication between the computers and microprocessors is provided by a data network and a synchronization timing system. Many of the design choices for this system have been dictated by the size and topology of the project. For example, the prohibitive cost of laying many dedicated cables around the 27 km circumference led to the decision to replace cables by a Time-Division Multiplex (TDM) system, which allows many communication channels on a single cable. The network is composed of two logical levels: the upper level consists of the central consoles and servers, which are situated in the control room, and the lower level consists of local consoles and process computers. This network is based on the Token Passing Ring principle (specification IEEE802.5) using TCP/IP as the high-level protocol.

The synchronization of control and data taking is a very important aspect of accelerator control. Two important examples of this are: firstly, the energy-ramping process, where all 750 power converters and the RF system must be controlled in perfect synchronization; and secondly, the acquisition, on the same machine revolution, of the closed-orbit data coming from the electrostatic pick-ups. The former example necessitates the use of the General Machine Timing (GMT) system, which consists of pulses at 1 ms intervals with coded events interlaced. The latter example requires the Beam Synchronous Timing (BST) system, which permits tagging of each of the eight bunches with a relative revolution number. This system allows the measurement and storage of the beam position for each bunch, at each pick-up, on a total of more than 1000 LEP revolutions. Measurements may be made over a much longer period by programming the BST to make measurements with a prescribed number of revolutions between each.

### 3.8 Injectors and pre-injectors

The LEP storage ring is the last accelerator in a chain of five, each of which handles the same electrons and positrons generated on every pulse by the electron gun and the positron converter. The LEP injectors consist of two linacs of 200 MeV and 600 MeV followed by a 600 MeV Electron–Positron Accumulator (EPA), which injects into the CERN Proton Synchrotron (PS) operating as a 3.5 GeV $e^+e^-$ synchrotron. The PS then injects into the CERN Super Proton Synchrotron (SPS), which operates as a 20 GeV electron–positron injector for LEP. The decision to use the two already existing CERN proton synchrotrons (the SPS and the PS) and all the infrastructure associated with them, resulted in significant economies both in cost and in time. The PS, originally designed for 28 GeV protons and commissioned in 1959, was modified to allow acceleration of electrons.
and positrons from 600 MeV to 3.5 GeV. The SPS, designed to accelerate protons to 450 GeV and first brought into operation in 1976, was modified to accept electrons and positrons from the PS at 3.5 GeV, accelerate them to 20.0 GeV, and finally transfer them to the LEP collider. In order to serve LEP with electrons and positrons, both the PS and the SPS operate in multicycle mode. In this mode, a supercycle is used which incorporates four cycles of electrons/positrons followed by one cycle of protons. Consequently, owing to the fact that the electrons/positrons are accelerated in the dead-time between the proton cycles, the filling of LEP has had little or no effect on the 450 GeV SPS stationary-target physics, which runs in parallel.

4. COMMISSIONING AND FIRST YEAR OF OPERATION

4.1 July and August 1989

The first injection into the LEP collider took place on 14 July 1989, one day earlier than scheduled. First collisions of electrons and positrons were provided almost exactly one month later, on 13 August 1989. In the following four months of interleaved operation for physics and machine studies the collider performance allowed more than 30,000 $Z^0$ particles to be detected in each of the four experiments. During 1990, the LEP performance allowed the detection of around 200,000 $Z^0$'s in each detector.

The speed and efficiency with which the LEP collider was commissioned was the result of careful planning and co-ordination of the testing of components as they were installed in the tunnel and, later, of the extensive programme of global testing without beam, just before the official turn-on date. In the nine months before July, all machine components had been installed and tested in situ in more than 24 km of the tunnel. This work involved in particular the installation of all magnets, vacuum chambers, RF cavities, beam instrumentation, the control system, injection equipment, electrostatic separators, electrical cabling, water cooling, and ventilation. The installation was followed by individual testing of more than 800 power converters and their connection to their corresponding magnets. Great care was taken to check and double check that all magnets had the correct polarity. In parallel, the vacuum chambers were baked at high temperature (either by superheated water or by electrical jackets) and then leak tested. The RF accelerating units situated around interaction regions 2 and 6 were commissioned and the cavities conditioned by raising them to their maximum power of 16 MW. Careful co-ordination of all work was essential in order to avoid conflicts between testing of the different systems and the transport needed for installation of the final octant 3–4.

In parallel with hardware installation and testing, a great effort, with limited manpower, went into the preparation of the software necessary for the operation of LEP. The software was prepared in close collaboration with the accelerator physicists and the collider operators. This allowed a clear definition of priorities so as to ensure that software became available as it was needed.

On 7 July, just one week before the scheduled switch on, the whole of the LEP collider was put through a complete 'cold check-out', which involved operation of all the accelerator components under the control of the available software. In particular, the energy ramping proved invaluable for the debugging of the complete system of hardware and software. The second cold check-out, scheduled for 14 July, turned out to be a 'hot check-out', since beams of positrons were already available from the SPS injector.

The period between 14 July and 13 August was, at the same time, crucial and exciting for the LEP collider. The accelerator work done during this period brought about the transition from the first successful completion of a single turn of the particles to com-
plete physics data taking. For this reason it is worth while itemizing the major accelerator milestones in their order of chronology.

14 July: Successful completion of a single turn by a beam of positrons.
18 July: Capture of the beam by the RF system. This gave around 100 turns.
20 July: Beam Orbit Monitoring (BOM) system used to measure and correct the single-turn trajectory. Measurement of the revolution frequency indicated that the LEP circumference is accurate to better than 1 cm.
22 July: Measurement and correction of the betatron tune values.
23 July: Circulating beam of positrons obtained with a measured lifetime of 25 min.
25 July: Successful injection of electrons.
30 July: Closed-orbit measurement and automatic correction. Accumulation of positrons, and first measurement of the effect of the beam on the vacuum pressure.
31 July: Synchrotron-light beam monitor commissioned, allowing ‘real-time’ observation of the beam cross-section.

1 August: Injection studies gave good accumulation rates and a record current of 500 µA.
2 August: Chromaticity correction with the six sextupole families.
3 August: Energy ramp to 47.5 GeV. Electrostatic separators commissioned.
5 August: Transverse impedance measured to be only 65% of estimated value.
8 August: Compensation of transverse coupling due to the experimental solenoids by use of the skew quadrupole system. Accumulation of record current of 850 µA with solenoids at nominal settings.
10 August: Energy ramp to 47.5 GeV followed by β squeeze to 42 cm under physics conditions.
12 August: Accumulation of both electrons and positrons.
13 August: Energy ramp and β squeeze to 32 cm, followed by stable beams for physics with 270 µA per beam.

Following the first stable beams run of 13 August, a pilot physics run was scheduled to cover a five-day period but, owing to various technical problems, only 15 hours of physics were possible during this period. Nevertheless, this pilot run allowed the ‘debugging’ of the experimental detectors with a maximum luminosity of $5 \times 10^{28}$ cm$^{-2}$ s$^{-1}$. About 20 $Z^0$'s per experiment were successfully detected during this period.

A period of three weeks of machine studies was scheduled after the first pilot physics run. The accelerator performance was greatly improved during this period. In particular, the low β was reduced to the ‘back-up’ design value of 20 cm, a new optics with less transverse coupling was commissioned, and injection studies gave higher filling rates and maximum intensities. The very last shift of this period was foreseen as a physics preparation run and gave a maximum total beam current of 1.6 mA at 45.5 GeV with the low β squeezed to 20 cm.

The first LEP physics run started on 20 September, slightly more than two months after the final testing of the installed accelerator components. The period between this first run and the Christmas shutdown was interleaved with physics data taking and machine studies aimed at increasing the luminosity. The physics running period was subdivided into three types of running. The first subperiod, lasting for five days, was scheduled for operating at the $Z^0$ peak (45.5 GeV per beam). During the second subperiod a mini-scan of the $Z^0$ was performed involving five different beam energies 0, ±1, and ±2 GeV (centre of mass) around the peak. The final and longest period was devoted to scanning the peak by spending 50% of the time on the peak and 50% off peak. The maximum luminosity
achieved during this period was $\sim 5 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, about one third of the design luminosity.

4.2 Operational performance during 1989 and 1990

The operational performance of the LEP collider has been continuously increasing since the first run in September 1989 (see Fig. 8). The integrated luminosity during 1990 is more than a factor of 7 higher than that achieved in 1989. It should be noted that the absolute values shown in Fig. 8 are optimistic by $\sim 20\%$ since the vertical blow-up due to the beam–beam effect has not been taken into account (see Section 5.1).

![Figure 8](image1.png)

Fig. 8 Evolution of the integrated luminosity during 1989 and 1990

![Figure 9](image2.png)

Fig. 9 Integrated luminosity per week during 1990
In Fig. 9 the integrated luminosity per week is shown for 1990. The best luminosity integrated over a period of one week in that year is in excess of 1750 nb\(^{-1}\), compared with the best value in 1989: 400 nb\(^{-1}\).

In Figs. 8 and 9 the average performance numbers are recorded; however, it is also useful to record the maxima so far achieved at LEP compared with design values. Table 1 gives such a comparison. Unfortunately not all maxima have yet been achieved simultaneously.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current per bunch (mA)</td>
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<td>0.750</td>
</tr>
<tr>
<td>Total current per beam (mA)</td>
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<td>3.00</td>
</tr>
<tr>
<td>Total current in both beams (mA)</td>
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<td>6.0</td>
</tr>
<tr>
<td>Vertical beam–beam strength parameter, (\xi_v)</td>
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<td>0.038</td>
</tr>
<tr>
<td>Horizontal beam–beam strength parameter, (\xi_h)</td>
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<td>0.038</td>
</tr>
<tr>
<td>Emittance ratio (\epsilon_v/\epsilon_h)</td>
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<td>0.040</td>
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<tr>
<td>Luminosity ((10^{39} \text{cm}^{-2} \text{s}^{-1}))</td>
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<td>16.0</td>
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<tr>
<td>Betatron amplitude function at the IP, (\beta^*_e) (cm)</td>
<td>3.7 (5.0)</td>
<td>7.0</td>
</tr>
</tbody>
</table>

5. PRESENT PERFORMANCE AND LIMITATIONS

5.1 The beam–beam strength parameter

During long physics runs at LEP, it has been observed that the specific luminosity \((L/\beta^*_e^2)\) increases as the intensity of the bunches decreases. This behaviour is shown in Fig. 10 and is due to the fact that, as the beam–beam strength parameter decreases with

![Graph 1](image)

![Graph 2](image)

Fig. 10 Measured specific luminosity and current product during a physics run
intensity, there is a reduction in the amount of vertical blow-up. From these results, one can calculate the vertical beam size and the beam–beam strength parameter as a function of beam intensity. These results are shown in Fig. 11. It is clear that the maximum value achieved is $\sim 0.016$, whereas the design value is 0.040. It is thought (and confirmed by beam–beam simulations) that this low value is caused by the fact that LEP is being operated at transverse tune values that are not optimized for beam–beam effects. The reason for operating at the present tune values is to minimize the betatron coupling arising from the residual skew quadrupolar fields due to the nickel layer.

![Graph](image)

**Fig. 11** Beam–beam strength and vertical beam size as a function of beam current

Recent beam–beam simulations of the LEP collider have shown that a significant increase in luminosity would be attained by operating LEP at tune values above 70 and 76 (horizontally and vertically respectively) instead of the values of 71 and 77 used at present. This new operating region will be tested during the first part of 1991.

In the 10 days of LEP operation immediately before this talk a significant effort went into equalizing the luminosities in all experimental areas. During these studies it was found that moving the 'waist' of the low-$\beta$ in interaction point 2 (IP2) improved the luminosity, not only in IP2, but to a lesser degree in all experimental areas (see Fig. 12). This is clear evidence that the vertical emittance was reduced by moving the waist in L3. Moving the waist varies the betatron phase advance between the collision points. Again beam–beam simulations had predicted such behaviour. Diagnostics and software capable of measuring the phase advance between the IPs to an accuracy compatible with maximizing the beam–beam strength parameter are being developed at present.
5.2 The intensity per bunch at collision energy

5.2.1 Transverse-mode coupling instability

In principle, the LEP intensity per bunch is fundamentally limited by the transverse-mode coupling instability at injection energy. Equation (18) shows that the threshold for the onset of this instability is proportional to the synchrotron frequency ($Q_s$). With a $Q_s$ equal to the operational value of 0.09, the onset of this instability is predicted (using actual measurements of the LEP transverse impedance and the beam) at around 0.80 mA per bunch. Such high values have not yet been attained operationally. During machine studies and using a higher value of $Q_s$ (0.135) the maximum intensity per bunch attained was 0.78 mA.

5.2.2 Synchro-betatron resonances

In practice, the intensity is limited in LEP by coupling between the synchrotron motion and the vertical betatron motion. Owing to the large amount of energy available in the synchrotron motion, this results in a large increase in the vertical dimensions in the beam and ultimately in a reduction in the beam lifetime. The maximum intensity is reached when the injection rate is balanced by the loss rate due to the poor beam lifetime. The synchro-betatron coupling is driven by dispersion at the RF cavities which converts energy gain into an increased betatron oscillation. For this reason the RF straight sections in LEP were designed to be dispersion-free; however measurements of the dispersion there indicate values of residual dispersion which are between a factor of 3 and $\sim$ 8 above expectation. The source of this residual dispersion is not yet fully understood. One basic limitation in the fight to reduce it is in its measurement, which cannot at present be operationally better than $\sim$ 10 cm r.m.s.

In 1991, with the improvements foreseen for the BOM system it should be possible to measure this dispersion down to 3 cm. In addition, an automatic procedure will be developed for correcting it.

5.2.3 Feedback systems and injection efficiency

a) Reactive transverse feedback

A transverse feedback system has been designed and installed in LEP to fight the transverse-mode coupling instability. This system can modify the coherent betatron-tune values so as to maintain them equal to the incoherent tune values. This would allow avoidance of synchro-betatron resonances independent of the bunch intensities. This system will be commissioned early in 1991.
b) Longitudinal feedback

The beams in LEP are longitudinally unstable for intensities over about 0.2 mA per bunch. In 1990 these instabilities were fought by the implementation of an ad hoc feedback system and the use of the damping wigglers. The disadvantage of this feedback system was that it required that the electrons and positrons had different values of $Q_s$, which greatly complicates the choice of suitable tunes to avoid synchro-betatron resonances. A new longitudinal feedback system has now been designed, which will treat each bunch individually and therefore not require different values of $Q_s$. This will be commissioned in 1992.

c) Injection at higher energy

If the injection energy of the SPS could be increased to around 22 GeV this would have an enormously beneficial effect on the maximum intensity which can be accumulated in LEP. The required upgrade to the SPS RF system is planned for the 1991–1992 shutdown.

5.2.4 Efficiency of energy ramping and $\beta$ squeezing

During 1990, measurements of the tune values during ramping indicated a large vertical tune 'jump' at the start and end of the ramp. This was still the case after using all foreseen techniques to compensate the tune shifts due to eddy currents induced in the vacuum chamber by the rate of rise of the dipole field. This tune variation was the cause of significant intensity losses at the start of the energy ramp, particularly at very high intensities. Towards the end of the running period it was discovered that this tune behaviour was due to the frequency response of the power converters feeding the superconducting low-$\beta$ quadrupoles. This problem was cured during the first weeks of the 1990–1991 shutdown. Consequently, losses at the beginning of the ramp should be insignificant thereafter. In addition to the fast tune variations at the beginning of the ramp, slower variations have been measured during the ramp. These variations have been compensated by updating the ramping files. The non-reproducibility of the tunes from one fill to the next are now taken care of by a 'tune control loop', which continuously measures the tune and compensates variations by adjusting the field in the main LEP quadrupoles. With the culmination of all these improvements in 1991, the energy ramping efficiency should approach 100%.

In 1990 the $\beta$ squeeze was performed with the beams in collision (i.e. with separators switched off). This was done in order to avoid the necessity of controlling the separator voltages during the squeeze. The result of squeezing in collision was that tune control was impossible owing to the large tune spread produced by the beam–beam effect. Towards the end of the 1990 running period the necessary modifications and tests were performed to allow squeezing with separated beams. This procedure is available for 1991 and will allow a significant improvement in the efficiency of the $\beta$ squeeze.

5.3 The betatron amplitude function at the collision point

During 1990 the $\beta_\ast^y$ at the collision points was successfully reduced from 7 cm to 5 cm for operation for physics. During machine studies the $\beta_\ast^y$ was reduced with low-intensity beams to a minimum value of 3.7 cm. In 1991 machine studies will be performed in order to commission a lower $\beta_\ast^y$ optics of, say, 4.0 cm. In addition, an attempt will be made to identify the minimum value of $\beta_\ast^y$ possible with the present LEP parameters, in particular the influence of the bunch length on this minimum due to beam–beam effects.
6. FUTURE PLANS

6.1 Energy upgrade

The future development of LEP to phase 2 has already been approved by the CERN Council and will take the beams up to energies that allow the study of W pairs. This will require the installation of 192 superconducting cavities from the beginning of 1990 till the first quarter of 1994.

As the thermal conductivity of these cavities is crucial for their quench behaviour, two lines of development have been followed. Firstly, niobium sheet metal with greatly improved thermal conductivity has been ordered from industry; secondly, a successful technique has been developed to sputter the inside surface of copper cavities with niobium. Although both types of cavities have already reached their design gradient of 6 MV/m, it is hoped that the copper–niobium type may reach even higher gradients, of 7–9 MV/m. Consequently, although the first 32 superconducting cavities to be installed will be of niobium sheet, it is intended that the rest will be of the copper–niobium type. For the cooling of these cavities, four cryogenic plants with an initial cooling power of 12 kW at 4.5 K, but designed for an ultimate capacity of 18 kW, will be installed at the even LEP points, following the cavity installation programme.

Whilst the production of the superconducting cavities is technically the most challenging aspect of the energy-increase programme, many other systems have to be upgraded. In particular, the superconducting low-β quadrupoles must be replaced, many power converters must be modified, new klystrons are required to provide the power, and klystron galleries must be dug at points 4 and 8. The successful completion of this project will allow experimenters to study the physics of W-pair production in 1994.

6.2 Number of bunches

By increasing the number of bunches per beam above the design value of four, a substantial increase in the LEP luminosity may be attainable throughout the operating energy range. Increasing the number of bunches, however, automatically increases the number of unwanted collision points and thereby would generate additional beam–beam problems. One way of separating the bunches at the unwanted collision points is by means of a ‘pretzel’ scheme. A preliminary feasibility study of such a scheme shows that, with respect to the design values of 4 bunches per beam and 0.75 mA per bunch, the luminosity could be increased by as much as a factor of 9 (by operating with 36 bunches per beam) if operation with the pretzel scheme has no negative influence on the maximum attainable current per bunch. In addition, by operating with 8 bunches per beam, a luminosity increase by a factor of 2 may be attainable at 90 GeV, if sufficient RF power is installed to replenish the beam power lost due to synchrotron radiation. For reasons of required beam power the pretzel scheme depends on the availability of the superconducting cavities foreseen for the energy upgrade.

Recently it has been decided that, from 1991 onwards, high-luminosity pp running in the SPS will cease to be a mode of operation. This has led to the possibility that the electrostatic separators used for this mode of operation could be recuperated for use in the LEP horizontal pretzel scheme. A crash study programme is under way to investigate the feasibility of such a scheme.

The goal of this study is to provide a pretzel scheme for testing and machine studies as early as the spring of 1992.
6.3 Polarization

Transverse polarization (at the level of around \(\sim 9\%\)) has been observed at the end of the 1990 run. During 1991 every effort will be made to increase the level of polarization and use depolarizing effects to calibrate the energy of the beams to an accuracy of \(\sim 50\) parts in a million.

Dedicated polarization wigglers have been ordered and will be installed in 1991. These will improve the polarization growth rate to a calculated 35 min.

Machine studies are planned to allow polarized beams in the presence of beam–beam forces and with the experimental solenoids operating normally. This will allow calibration of the beam energy during each LEP physics fill.

Longitudinal polarization, obtained by rotating the polarization through 90\(^\circ\), would enable the very precise study of the weak couplings at the \(Z^0\) peak. Spin rotators have been designed and could be installed, provided the outcome of the transverse-polarization studies is favourable.

7. CONCLUSIONS

From a hardware point of view, LEP phase 1 has been successfully completed and every effort is now being made to increase the luminosity up to and hopefully beyond the design value. The future development of LEP to phase 2 has already been approved by the CERN Council and will, as previously stated, take the beams up to energies that will allow the study of \(W\) pairs.

The present LEP collider, with its energy upgrade and the future programmes of higher luminosity and polarization, is providing and will continue to provide for the physicists of Europe and the rest of the world, a unique and powerful physics tool for fundamental research in the 1990’s.

Acknowledgement

This lecture is an overview of the work done by a very large number of scientists and technicians who dedicated a large fraction of their professional life to the successful design, construction, and commissioning of the LEP collider. More detailed information on the individual contributions can be found in specialized reports at many conferences on accelerator physics, for example The European Particle Accelerator Conference held in Nice in June 1990.