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AVANCÉES EN PHYSIQUE DES PARTICULES : LA CONTRIBUTION DU LEP

ADVANCES IN PARTICLE PHYSICS: THE LEP CONTRIBUTION

The LEP collider

Roger Bailey, Cristoforo Benvenuti, Steve Myers, Daniel Treille *

CERN, CH-1211 Geneva 23, Switzerland

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Abstract The LEP collider and the performances which have been achieved are presented in simple terms. Some basic facts of electron circular machine physics are recalled. The ambitious and very successful programmes undertaken to maximize LEP luminosity and energy are described in detail. ***To cite this article: R. Bailey et al., C. R. Physique 3 (2002) 1107–1120.***

luminosity / synchrotron / superconducting radiofrequency cavities / ultra high vacuum / getter pump

L’anneau de collisions LEP

Résumé Le collisionneur LEP et ses performances sont présentés en termes simples. Quelques éléments de la physique machine d’un collisionneur circulaire à électrons sont rappelés. Les deux batailles, pour la luminosité et pour l’énergie maximale, que le LEP a menées et gagnées sont décrites en détail. ***Pour citer cet article : R. Bailey et al., C. R. Physique 3 (2002) 1107–1120.***

luminosité / synchrotron / cavités haute fréquence supraconductrices / ultravide / pompage intégré

1. Introduction and brief history of LEP

The idea to build a high energy electron–positron collider appeared in a note by B. Richter, a visitor to CERN, in March 1976 [1]. The experimental possibilities were described and a cost minimisation technique developed, leading to the conception of a machine that could operate up to a centre of mass energy of 200 GeV.

Financial, geological and political arguments caused the circumference and the maximum beam energy of LEP to oscillate for a time. In the Blue Book of 1978 they were 22.2 km and 100 GeV, in the Pink Book of 1979 30.6 km and 130 GeV, and finally in the LEP Design Report of 1984 26.67 km and 125 GeV.

Fig. 1 shows the planning for the LEP project as presented by J. Adams at the workshop held at Les Houches in 1978.

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* Corresponding author.
E-mail address: Daniel.Treille@cern.ch (D. Treille).

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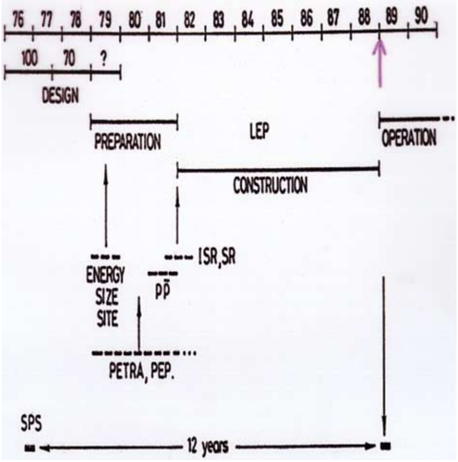

Figure 1. The LEP planning, ten years in advance.

In 1982 the LEP project was authorised with the full, unconditional support of all the Member States. Meanwhile the LEP team had continued to work on the optimisation of different aspects of the project and on the choice of the exact implementation of the machine. It was decided to incline the plane of the tunnel. An active R/D program on the radio-frequency cavities, both warm and superconducting, was already underway.

In 1983 the 'Déclaration d'Utilité Publique' for LEP was signed and civil engineering could commence. The same year, the Z^0 particle was discovered, with a mass around 92 GeV, very close to theoretical predictions and well within the range accessible at LEP.

From 1986, ideas concerned with what to do after LEP, namely the LHC (centre of mass energy of 17 TeV with a luminosity of 10^{33} $\text{cm}^{-2}\cdot\text{s}^{-1}$) were clearly defined.

In February 1988 the excavation of the LEP tunnel was finished, and in the summer of 1989 the first Z^0 particles were recorded in the four experiments, less than six years after work started. For more on the history of the LEP, see [2–5].

2. General description of the machine

The LEP ring [6] extends from the foot of the Jura to Geneva airport, straggling the French–Swiss border. The 3.8 m diameter tunnel is all underground, at a depth which varies from 50 to 175 m. The ring of 26.67 km circumference is composed of eight 2.9 km long arcs and eight straight sections extending 210 m on either side of the eight possible collision points. At four of these points the experiments were housed in their underground caverns. Approximately 3400 dipoles, 800 quadrupoles, 500 sextupoles and more than 600 orbit correction dipoles were installed in the LEP ring. The lattice was of type FODO (Focussing quadrupole–dipole–Defocussing quadrupole–dipole) with a periodicity of 79 m, with 31 such cells per octant. The angle of deviation per cell was 22.62 mrad.

At LEP the critical factor determining the circumference was the problem of synchrotron radiation, which consists of the emission of photons due to the transverse acceleration experienced by the electrons on their curved orbit. The energy radiated is proportional to the fourth power of the energy of the particles and inversely proportional to the radius of curvature in the dipoles, which implies a circumference as large as possible. The strong dependence of this loss as a function of energy places severe limitations on the maximum energy that one can obtain with a circular electron collider, and LEP200 will probably be the last of its kind on the high energy frontier. On the one hand the energy lost has to be replaced by the radio-frequency (RF) system, while on the other hand the different components around the machine have to withstand the power deposited by the synchrotron radiation. In LEP at 100 GeV, the radiated power for a total intensity of 6 mA was around 18 mW. At 104 GeV some 3% of the beam energy was lost each turn.

The RF system was installed in the straight sections around each experiment. Firstly warm copper cavities were installed, sufficient to allow LEP to function at an energy corresponding to Z^0 production, the so-called LEP1 phase. Later these were progressively replaced and supplemented by superconducting cavities (SC), which we describe later in detail, in order to achieve the energies of LEP200. At the end of machine operation, the SC system consisted of 288 four-cell cavities, operating at 352 MHz, powered by 36 klystrons each giving a mean of 0.6 MW of RF power. This system was augmented by 56 of the original copper cavities, providing ∼130 MV. The total acceleration voltage achieved was 3630 MV. Considering that the active cavity length was 1.7 m (two RF wavelengths), this corresponds to an average cavity field of $7.5\ \mathrm{MV \cdot m^{-1}}$.

Certain remarkable aspects of the machine are now described.

2.1. Civil engineering

Chronologically the construction of LEP began with civil engineering and infrastructure work. This represented more than half of the total construction budget, and from 1983 to 1988 constituted the biggest civil engineering project in Europe. It is particularly satisfying that the LEP tunnel and a large part of the associated infrastructure will be reused for the LHC.

This gigantic work was also subtle, underlined by the fact that the ‘moles’ used to dig the tunnel were guided round their trajectories to a precision of 1 cm.

As well as the underground works, it was necessary to construct 71 surface buildings, totalling some $51\,000\ \mathrm{m}^2$ over the eight sites. Furthermore this work was realised in such a way as to preserve the local environment in a satisfactory way.

2.2. The magnets

To make 100 GeV electrons circulate in a ring as large as LEP is easy from the point of view of the electro-magnetic force required, needing a field of only 0.1 T. This allowed some innovation on the design of the core, filling with cement the 4 mm spaces between the 1.5 mm steel laminations. Compared to a classic scheme, this technique brought an economy of around 40%.

At the other end of the scale, the bunches of each beam have to be very strongly focussed in the centre of the detectors in order to maximise the luminosity of the collisions (see below). This was achieved by extremely strong superconducting quadrupoles operating with very high field gradients.

The alignment of the components of the collider was realised with a relative precision of better than 0.1 mm. The first precise measurement made with beam showed that the circumference of LEP was in fact twice as good as predicted: better than 1 cm in 26.67 km.

2.3. The vacuum

The typical duration of a data taking run in LEP was 10 h at the Z^0 energy. During these ten hours some 10^{12} particles would make around 400 million turns. In order to minimise the losses coming from collisions with the residual gas, the vacuum chamber had to be kept at an extremely low pressure, 10^{-9} Torr during operation of the machine, which implies a value as low as 10^{-11} Torr in the absence of outgassing on the surface caused by synchrotron radiation.

As well as a classic pumping system, based on turbomolecular pumps, a new type of ultra-high vacuum system was devised and installed, for the first time in an accelerator [7]. This consisted of a Non-Evaporable Getter (NEG) strip, installed in pumping channels parallel to the beam pipe, with pumping holes between, and extending over about 23 km. The material of the NEG was a constantan strip coated with an alloy of Al–Zr, which forms stable chemical compounds with most of the active gases [8]. Consequently the residual gas molecules simply ‘stick’ to the NEG ribbon. A periodic regeneration of the getter was necessary, involving heating to 400 degrees C. The NEG fulfilled its function perfectly, even when the increase in the energy of LEP meant an increase in the degassing rate by a factor 16.

With such a vacuum quality, the beam lifetime in LEP was determined by factors other than interactions with the residual gas, such as radiative diffusion and the inverse Compton effect.

2.4. The accelerating system

The role of the RF system is on the one hand to accelerate the particles from the energy at which they are injected (20 then later 22 GeV) to the energy needed for physics, and on the other hand to replace the energy lost due to synchrotron radiation [9–14].

The general idea of acceleration is to use a stationary radio-frequency wave, composed of a longitudinal oscillating electric field. The particles are already grouped into bunches before injection in such a way that they arrive with the correct phase with respect to the RF field. The operating frequency of the cavities is 352.209 188 MHz, which corresponds to 31 320 times the revolution frequency in LEP, f_{rev}. In principle, a total of 31 320 bunches is possible. In reality, one wants only the small number that would collide in the experiments, without unwanted collisions at other points. With four experiments, the smallest number is two bunches per beam; the initial choice was four equidistant bunches per beam, with separation at the four unwanted collision points. It is necessary to inject and accumulate only the desired bunches, which implies a very precise synchronisation system between the RF system of LEP and its injector, the SPS. In these conditions the bunches meet every 22 microseconds in the experiments, a very comfortable situation.

Originally, the RF system consisted of 128 five-cell copper cavities, powered by 16 klystrons of 1 MW (maximum value, the mean value delivered was 0.6 MW) via a complex of waveguides and circulators, which protect the klystron from reflected power. Each accelerating cavity was coupled to a spherical low-loss storage cavity in such a way that the electromagnetic power continuously oscillates between the two sets of cavities. The coupling was arranged such that the power was at its peak in the acceleration cavity 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 its time in the low loss storage cavities.

The accelerating field of these cavities was of order 1.5 MV per meter, and the peak accelerating voltage 400 MV per revolution.

That was sufficient for LEP1, spent at beam energies around 45.6 GeV. To attain higher energies one had to turn to superconducting cavities, of a new type and at new performance levels (nominally 6 and finally 7.5 $\mathrm{MV \cdot m^{-1}}$). The conception and the realisation of a large number of such cavities constituted the major technological adventure for LEP, and is described in Section 5.

2.5. Injectors and pre-injectors

The LEP storage ring was the last accelerator in a chain of five, each of which handled electrons and positrons generated on every pulse by the electron gun and the positron converter (Fig. 2). The pre-injector, LIL, was developed in close collaboration with the Laboratoire de l’Accélérateur Linéaire d’Orsay. Re-using the existing machines, PS (Proton Synchrotron, commissioned in 1959) and SPS (Super Proton Synchrotron, commissioned in 1976), with appropriate modifications, as injectors for a new machine is a CERN tradition which contributes considerably to reduce the cost of projects, and will be the case again for the LHC.

Considering the complexity, the performances of LEP in terms of reliability were remarkable. As an example, in the year 2000, the total time that LEP did not have beam, for any reason including power cuts, was 383 hours out of 5107 scheduled, a down time of only 7.5%.

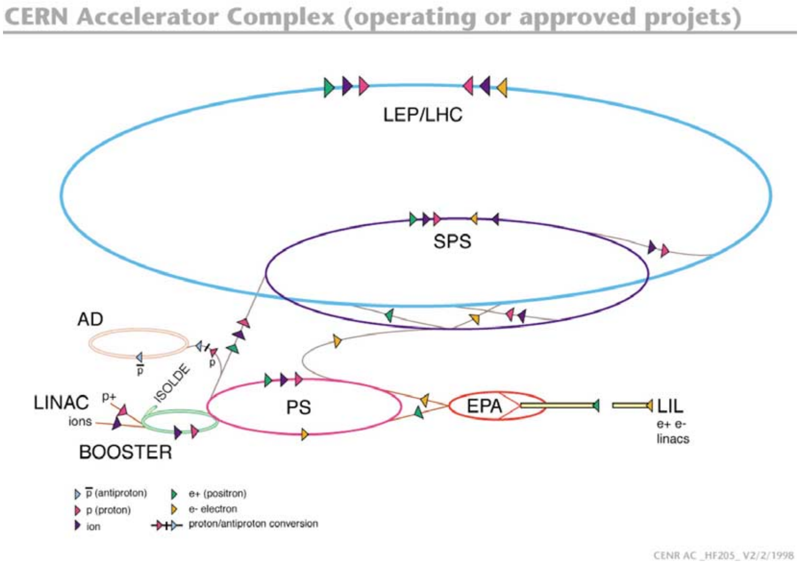

Figure 2. The complex of LEP injectors.

2.6. The control system and beam instrumentation

Each component of LEP, or almost, had to be controlled remotely from the main control room. The control system comprised more than 160 computers and microprocessors distributed over 24 underground zones and 24 surface buildings. The technical choices were mostly dictated by the size and topology of the project.

To control the beams, it is necessary to observe their position, their shape and other important parameters. During normal operation it is impractical to rely on monitors placed directly in the beam, and other means are required. Over 500 electrostatic 'buttons', each with 4 pick-ups, distributed around the ring allow us to deduce the horizontal and vertical positions of the bunches. Other dedicated electrostatic pick-ups allow, for example, the measurement of the number of oscillations per turn, Q (see below), after exciting the beam with a magnetic 'shaker'.

The synchrotron light contributes information used to measure the profiles of the beams. It serves also to measure the length of the bunches with picosecond precision.

The synchronisation of control and data taking is an important aspect of the problem, since one wants to know the energy and exact position of the bunches for each physics event produced.

2.7. Protection against 'background'

With $\sim 10^{12}$ electrons in the machine, each making $\sim 10^4$ turns per second and emitting $\sim 13\,000$ photons per turn (at 100 GeV or more), the number of photons emitted is phenomenal (10^{20}) and it is necessary to protect both elements of the machine and the detectors. A complex system of collimators was designed to intercept the photons, not forgetting accommodating the increase in energy. This system also had the role to prevent particles lost from the beams, due to an energy fluctuation for example, arriving in the detectors. This work was ongoing throughout the life of LEP, requiring a close interplay between the machine and the detectors.

2.8. The cost of LEP

The LEP collider (tunnel and LEP1) cost 1131 million Swiss Francs (1981 prices), compared to the initial estimate of 890 million. The investment was financed by 14 member states over a period of 10 years. The experiments cost 480 million Swiss Francs, of which CERN paid 140 millions. The remaining 340 millions came from outside institutes and universities. North America, Russia, China and Japan all contributed to the construction of the experiments. The cost of LEP200 was a further 400 million Swiss Francs. It is estimated that 2000 man-years has been invested in the whole project.

3. A little accelerator physics

3.1. The optics of LEP

In a collider or storage ring, the curvature of the particle trajectories is obtained by dipole magnets, while at the same time the particles are focused and maintained on a stable closed orbit by quadrupole magnets. As it travels through the accelerator lattice, each particle performs oscillations around the closed orbit, so called betatron oscillations. The number of oscillation periods is called the betatron tune Q. For LEP Q varied between 60 and 100 depending on the machine optics. As the beam energy is increased, a stronger focusing becomes more favorable, leading to a higher Q value.

Furthermore each particle performs coupled energy and longitudinal oscillations relative to the average energy and azimuth. Those oscillations are called synchrotron oscillations. The electric field of the accelerating cavities produces a potential well inside which each particle performs stable synchrotron oscillations. Particles at the centre of this potential well are called synchronous particles.

For a perfect accelerator and a perfectly monochromatic beam the betatron tune can a priori take any value. In reality, the choice for Q is limited due to machine imperfections and beam parameter spreads. Care must be taken to avoid certain ranges of Q values which would lead to beam instability due to the cumulative effect of their perturbations. The choice of Q values is further limited by the unavoidable coupling between horizontal and vertical planes. Longitudinal synchrotron oscillations can also couple to the transverse planes and lead to synchro-betatron resonances. A typical cause for such coupling is non-vanishing dispersion at the location of accelerating cavities.

3.2. Synchrotron radiation and its effects

Synchroton radiation is emitted by the electrons under the influence of transverse acceleration. The energy spectrum of the photons, which are emitted along the direction of flight of the electrons, is characterized by its critical energy:

$$E_c \propto \frac{E_b^3}{\rho}, \tag{1}$$

where ρ is the curvature of the orbit and E_b is the beam energy. At a beam energy of 45.6 GeV corresponding to the Z^0 resonance, the critical energy is 70 keV, at 100 GeV it is 733 keV.

For one Tesla-meter of integrated dipole field an electron emits on average 6.2 photons with an average energy of 0.31 E_c. On one LEP turn this represents $\sim$13 000 photons at 100 GeV. The energy loss per turn for each particle is:

$$U_0 = \mathrm{C}_\gamma \frac{E_b^4}{\rho}, \tag{2}$$

where C_γ is 8.86×10^{-5} m·GeV^{-3}. At 100 GeV U_0 reaches $\sim$3 GeV.

For a beam of k_b bunches of current I_b, the power lost by synchrotron radiation is:

$$P_b = 8.86 \times 10^{-2} \frac{E_b^4 k_b I_b}{e\rho}\ \mathrm{MW} \tag{3}$$

which corresponds to 18 MW for a total beam current of 6 mA at 100 GeV.

On one hand this energy loss must be compensated by the accelerating cavities, but on the other hand the components must be able to absorb the dissipated power.

A beneficial aspect of synchrotron radiation is the fact that it damps betatron and synchrotron oscillations. In a simple and somewhat approximate view, the damping can be explained by a geometrical argument: the energy loss by synchrotron radiation is collinear to the trajectory while the energy gain is entirely longitudinal. The vertical amplitudes are strongly damped. Due to the presence of dispersion in the horizontal plane, the phenomena are more complex. A particle having lost some energy will also start an oscillation around a displaced closed orbit with a corresponding change in the betatron amplitude.

The damping of the synchrotron oscillations is the result of the dependence of the energy loss on the particle energy, a higher beam energy leading to a stronger energy loss.

The damping which is present in all three planes can be characterized by three damping times

$$\tau_i = 2\frac{E_b}{J_i U_0 f_{\mathrm{rev}}}, \tag{4}$$

where i labels the three coordinates. J_i is the damping partition number for a given plane. The values of the damping partition numbers can be varied, but their sum is fixed to 4.

The emission of synchrotron radiation is a quantum phenomenon which concerns a vast range of photon energies. The beam energy spread is the result of an equilibrium between damping and quantum excitation due to the photon energy fluctuations about the average beam energy. When the energy spread is too large and approaches the energy acceptance of the accelerator which is typically a few percent, the energy fluctuations can lead to particle losses. At very high energy, the acceptance is mainly limited in the longitudinal plane by the available accelerating fields, and the lifetime associated to those longitudinal losses is called the quantum lifetime.

3.3. Maximum energy of the machine

The energy lost by the beam is compensated by the RF acceleration system. The RF voltage oscillates at high frequency in the RF cavities (352 MHz for LEP) and is synchronized to an integer multiple h of the revolution frequency. The bunches pass the RF cavities with a phase ϕ_s relative to the RF voltage and the energy loss is compensated when

$$U_0 = eV \sin\phi_s, \tag{5}$$

where V is the peak voltage. V is given by the product of the average accelerating gradient E_{acc} and the total length of the RF system.

An over-voltage $q = 1/\sin\phi_s$ is required as margin against large fluctuations of the energy loss in order to maintain a sufficiently high quantum lifetime.

Besides the RF voltage, other parameters only play a minimal role in the maximum energy reach of the accelerator. The highest beam energy is therefore mainly given by the number of RF cavities and their average field gradient.

3.4. Luminosity

Besides the highest beam energy which determines the largest mass for a newly created particle, the other crucial parameter of the accelerator is its luminosity L. The total number of events produced per unit time interval for a process when a cross section S is given by

$$\frac{\mathrm{d}N}{\mathrm{d}t} = LS. \tag{6}$$

The goal of LEP was to deliver the highest possible event rate at various center-of-mass energies, therefore maximizing the luminosity.

The luminosity of two beams $+$ and $-$ with Gaussian profiles is:

$$\mathcal{L} = \frac{N_{b+} N_{b-} f_{\text{rev}} k_b}{2\pi \sqrt{(\sigma_{x+}^2 + \sigma_{x-}^2)(\sigma_{y+}^2 + \sigma_{y-}^2)}}, \tag{7}$$

where k_b is the number of bunches per beam and N_b is the number of particles in each bunch (typically 10^{11}). σ represents the rms transverse horizontal (x) and vertical (y) beam sizes. Their typical values range from 100 to 300 microns in the horizontal, and 2 to 6 microns in the vertical plane. This equation for the luminosity assumes that there are no transverse offsets between the beams at the collision point. In praxis those offsets are minimized and their effect can in general be neglected. This equation can be simplified further for beams with equal sizes, which is a good approximation in most cases.

3.5. The beam–beam interaction

The electromagnetic field associated with each bunch influences the particles of the counter-rotating beam whenever they pass each other. For small transverse offsets this field varies linearly with the distance. At larger offsets the fields become non-linear which can lead to beam instabilities, large growth of the beam sizes and heavy background in the experiments. The beam–beam force is described by its linear component ξ which leads to a spread in the tune value Q of the same amount. For head-on collisions of flat beams ($\sigma_y \ll \sigma_x$) ξ scales in the following way with beam energy, machine tune and bunch population:

$$\xi_y \sim \frac{Q_x^3 N_b}{E_b^3}. \tag{8}$$

Obviously the effect of the beam–beam forces increases with the bunch population and with the horizontal focusing which leads to a strong reduction of the horizontal beam sizes. Furthermore the beam–beam effects become more important at lower energy due to the reduced stiffness of the beams. As a consequence the beams must be well separated at the collision points during the injection process using electrostatic separators. The beam–beam effects are still very strong for beam energies around the Z^0, but it weakens significantly at LEP200.

In a regime of strong beam–beam the luminosity can be expressed as:

$$\mathcal{L} \propto \frac{N_b f_{\text{rev}} k_b E_b \xi_y}{\beta_y^*}, \tag{9}$$

where β_y^* is the vertical betatron function at the interaction point, which will be discussed in more detail in Section 4.3.

In a regime of strong beam–beam the luminosity will be maximized for the highest achievable beam–beam tune shift. In fact in this regime, the beam–beam tune shift remains constant over a relatively large range of bunch currents.

There a 3 regimes for the beam–beam effects:

- at low bunch currents, the beam–beam effect is weak and the luminosity grows approximately with the square of the bunch current;
- above a certain threshold, the beam–beam force blows up the beam sizes to maintain a constant beam–beam tune shift: at LEP1 this value was around 0.04. In this regime the luminosity grows linearly with the bunch current. This is called the ‘soft’ beam–beam regime which must be maintained by various operational procedure to optimize the luminosity;
- beyond this soft regime, the beam size blow up grows beyond the available aperture and the lifetime of the beams degrades dramatically. In parallel, backgrounds in the experiments becomes intolerable.

To maintain a constant beam–beam tune shift, the beam emittances are often deliberately increased using special wigglers magnets installed in dispersive regions. Furthermore the beam intensities must be well balanced to avoid a 'flip–flop' state where the stronger beam destabilizes the weaker beam.

3.6. The two battles of LEP

The energy dependence of the beam–beam tune allows us to separate the LEP operation into two distinct phases.

At beam energies around the Z^0 (45.6 GeV) the target was to collect the largest possible number of Z^0's to improve the statistical and systematic errors on tests of the Standard Model and to observe the largest possible number of heavy flavor particles. At those energies LEP was in a luminosity regime around the soft beam–beam limit where beam–beam tune shift was constant during most of the duration of physics data taking periods. Measures taken to enhance the luminosity in this regime are described in Section 4.

At LEP200 the goal was to achieve the highest possible energies, limited mainly by the number of SC cavities, while at the same time maintaining a good luminosity. At LEP200 the luminosity was mainly determined by the bunch currents and the transverse beam sizes, both horizontal and vertical, which were optimized by different techniques. The optimization of energy and luminosity will be described in Sections 4 and 5.

4. The battle for luminosity

Inspection of the luminosity formula above suggests three ways to increase luminosity.

4.1. Increase the number of bunches

For a collider with n_c collision points, the minimum number of bunches needed is $n_c/2$. Increasing this number implies:

- controlling beam–beam effects: these are inevitable at the desired collision points, but one must eliminate the other parasitic ones. It is therefore necessary to separate the beams at the unwanted collision points. This was done in the vertical plane by using electrostatic separators;
- increasing the RF power: this becomes prohibitive at high energy;
- adapting the detectors to the rhythm of the collisions: within certain limits this posed no problems for the experimental physicists. For the first year, 4 bunches per beam were used, with separation as described at the unwanted collision points. To go further, following a workshop held in 1990/91, two approaches were pursued;
- the 'Pretzel' scheme, which takes its name from the biscuit, consists of making beam orbits with an oscillating structure, in opposite directions for the two beams, so that they avoid each other everywhere except at the collision points for physics. This is easier to do in the vertical plane. However the number of separators needed and the residual beam–beam effects rises quickly with the number of bunches. The scheme used at LEP had eight equidistant bunches per beam, and was used from 1992 to 1994;
- the bunch train scheme, which evidently consists of making trains of bunches, with the spacing between bunches in a train very small compared to distance between the trains. This scheme was used from 1995, initially with four trains of three bunches, then later with four trains of two.

4.2. Increase the current per bunch

Here other effects, namely collective effects, restrict us going too far in this direction. The particles in a bunch constitute a considerable charge and a current that act as a source of electro-magnetic fields. These, depending on the limiting conditions imposed by the environment (vacuum chamber, RF cavities, etc.), can react back on the beam. The nature and amplitude of this effect depends on the impedance of the section of the accelerator considered. In particular the copper cavities, of relatively low quality factor, are particularly dangerous.

The most serious effect is an instability due to the transverse force created by the particles at the head of a bunch, which then excites the particles in the tail. The current limit from this instability is lowest at low energies, and so is a limitation at injection. Remedies in LEP consisted, among others, of increasing the injection energy from 20 to 22 GeV by modifications to the RF system in the SPS, and of a reduction in impedance in LEP, which came in part by removal of many of the copper cavities during installation of the superconducting modules. The ultimate limit reached in LEP was around 1 mA per bunch at injection.

4.3. Minimise the transverse beam size

These dimensions depend on the transverse emittance and the betatron amplitude function. Emittance is a concept describing the quality of the beam in terms of the volume in phase space that it occupies. The betatron amplitude is a quantity related to the optics and varies around the ring. At the interaction point, it is denoted β^*. If the dispersion is zero, the beam size at the collision point if given by:

$$\sigma_z^* = \sqrt{\beta_z^* \varepsilon_z}, \tag{10}$$

where $z = x, y$. With dispersion this becomes:

$$\sigma_z^* = \sqrt{\beta_z^* \varepsilon_z + \left(\frac{D_z^* \sigma_e}{E_b}\right)^2}, \tag{11}$$

where D_z^* describes the local sensitivity of the position to a change in energy, and σ_e is the energy spread in the beam.

One can therefore reduce the beam size by reducing the betatron function at the collision point. This is done by increasing the strength of the quadrupoles around the interaction region, and superconducting quadrupoles of high gradient (up to 55 Tm^{-1}) were installed to this effect.

Other than the maximum gradient, there are other limits to the minimum value of β^*. In the vertical plane β_y^* must be at least two times bigger than the bunch length, which is typically 1 cm. Furthermore the chromaticity resulting from the non-linear focussing of the quadrupoles has to be corrected by sextupoles, and strong sextupoles can make important perturbations of the optics. In the horizontal plane, the minimum value of β_x^* is limited by experimental background considerations because a small value at the interaction point implies a large beam size in the closest quadrupoles. The values initially foreseen are compared to those finally achieved in Table 1.

The horizontal emittance, as already shown, is determined by the damping coming from synchrotron radiation. One can show that

$$\varepsilon_x \sim \frac{E_b^2}{J_x Q_x^3}, \tag{12}$$

where J_x, one of the three numbers mentioned above, characterises the damping in the horizontal plane. One sees that the emittance increases with the square of the energy, but that one can reduce it by making use of a stronger focussing lattice and by increasing the horizontal damping partition number.

While the vertical emittance should be greatly reduced by damping, there inevitably exists couplings between horizontal and vertical planes and a residual dispersion, due to dipole errors and the vertical separation bumps. It is the residual terms that dominate, and after good coupling correction, it is the vertical dispersion that limits the vertical beam size. At LEP the optimisation of this parameter was first made empirically, and later by a more systematic method. At the end of LEP the vertical emittance was so well optimised that it was sensitive to movements of the vertical orbit at the 20 micron level. The ratio of the vertical and horizontal emittances, which should be as small as possible, is given in Table 1: LEP did ten times better than foreseen.

Table 1.

	Foreseen (55/95 GeV)	Achieved (46/98 GeV)
Current per bunch	0.75 mA	1.00 mA
Total current	6 mA	8.4 mA/6.2 mA
Beam–beam vertical parameter	0.03	0.045/0.083
Ratio of emittances	4.0%	0.4%
Maximal luminosity (10^{+30})	16/27	34/100
β_x^*	1.75 m	1.25 m
β_y^*	7 cm	4 cm

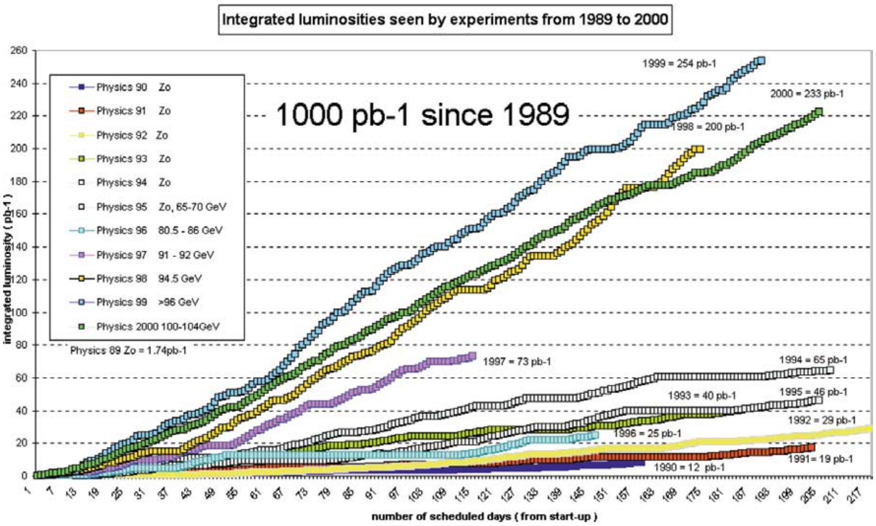

Figure 3. Summary of LEP performances.

4.4. The result

Table 1 compares the luminosity foreseen and that finally achieved. The result is remarkable: LEP performed between two and four times better than expected. The record peak luminosities, at the start of a physics run, were $34 \times 10^{+30}$ $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ at LEP1 and $100 \times 10^{+30}$ $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ at LEP200. Fig. 3 summarises the performance of LEP over 12 years of operation.

At LEP200, where increasing the number of bunches was not possible, the third weapon, reducing the vertical beam size, brought great rewards and resulted in luminosities four times higher than those foreseen.

5. The LEP200 energy battle

5.1. Superconducting cavity design

For the increase in energy the replacement of the warm cavities by superconducting cavities was an absolute necessity. To operate LEP at 103 GeV with classical cavities would require 1280 of them, with 160 MW of RF power, which makes no sense for many reasons.

Early on, the superconducting cavities were made from niobium sheets. Their accelerating field was limited by dramatic losses of the superconductivity (a 'quench'), due to the local heating of the surface in the presence of defects. Development work brought improvements in the purity of the niobium, increasing the thermal conductivity at liquid helium temperature and containing the temperature increase induced by the defaults.

An alternative solution consists of replacing the niobium by copper for the body of the cavity, and depositing a thin layer of niobium ($\sim$1 micron) on the copper (Fig. 4). As well as an important gain in material costs, mechanical stability, stability against a quench, the quality factor and insensitivity to small magnetic fields all contribute in the right direction.

This was the solution chosen and developed at CERN from 1980. The niobium coating was done by sputtering using a magnetron configuration. One of the major problems was the preparation of the substrate before coating. Any contamination had to be avoided. To give some idea, a cavity of surface $\sim 6\ \mathrm{m}^2$ had to be as clean as the silicon slices of surface $20\ \mathrm{cm}^2$ used in VLSI integrated circuits! It was also necessary to develop the associated cryogenics, in particular the cryostat where the design necessitated the introduction of new construction concepts.

Note in passing that the techniques of non-evaporable getter pumping (see Section 2.3) and the deposition of the niobium, by the same inventor, were combined to produce thin coatings of NEG, used in diverse applications, in particular for ultra-high vacuum systems.

5.2. Industrial production

Once the above points were resolved, the major challenge was to help industry to quickly master a number of new technologies, such as electron–beam welding, ultra-high vacuum, chemical cleansing, niobium sputtering, clean-room operations etc. Inevitably several difficulties were encountered, too numerous to mention, but following an excellent collaboration, the new technologies developed at CERN became an industrial reality. Three European companies, one of them French, produced the 288 cavities (20 of which were solid niobium) within the required specifications. Thanks to the technology transfer, these companies are now able to use the techniques mentioned and exploit them for their own gain.

5.3. The outcome

The nominal acceleration field required was $6\ \mathrm{MV{\cdot}m^{-1}}$, and the cavities received from industry all fulfilled this condition. As already mentioned, for a given field, the number of cavities determines the maximum accessible energy. One regret of the LEP physicists is that the number was limited to 288, while a further 80 to 100 cavities could have been accommodated in the accelerating sections without prohibitive civil engineering work. On the other hand, once several initial problems has been mastered, such as the

Figure 4. A superconducting cavity, cut in two. One can see the inner layer of sputtered niobium.

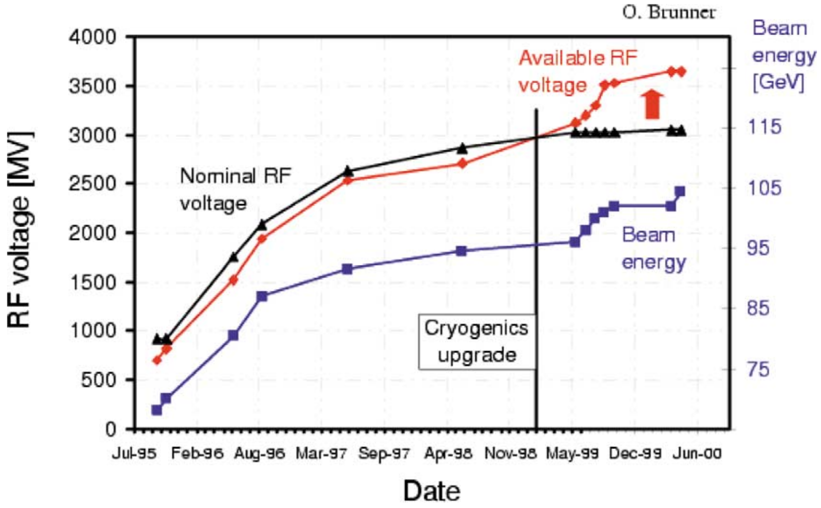

Figure 5. Evolution of the accelerating voltage at LEP200.

RF power couplers or the ponderomotive oscillations (a coupling between the stored RF energy and the mechanical oscillations due to the Lorentz force, or radiation pressure, on the surface) a magnificent effort, led by the RF specialists, saw the end of the LEP program with an average field of 7.5 MV·m^{-1} compared to the 6 MV·m^{-1} specified. This gain was to a large extent the result of cavity conditioning, first rather prudent, then more bold through pulsed power processing. Fig. 5 shows the result of this program, along with an improvement in the cryogenics already foreseen for the LHC. Once more LEP became better than foreseen.

Furthermore the whole system functioned in a very stable manner, at least up until it was asked to perform at the limit of its capabilities.

The only regret was to have lost the possibility to attain, through the addition of more cavities, a centre of mass energy $\sim$7% higher. This may not seem much, but if one refers to the article treating the lightest supersymmetric Higgs boson [15], one sees that this could have been decisive in proving its existence.

6. Conclusion

One conclusion to be drawn from this issue on the physics is that LEP, in electroweak and in heavy flavour, in particular beauty physics, produced better results, often much better results, than the most optimistic estimates. We would like to underline that this ‘nice surprise’ is due in no small part to the excellent performance of the machine, which in itself was much better than foreseen. The high luminosity delivered is reflected directly in the statistical and systematic precision of the electroweak measurements. Even the successes which seems to belong to the detectors, such as the quality of the B-tagging by the microstrip detectors, are only possible thanks to the cleanliness of the delivered beam and the low level of background in the machine. The experimentalists of LEP recognise the numerous ‘tours de force’ achieved by their colleagues from the accelerator, and express their profound gratitude for a magnificent decade of physics.

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