A Brief History of the LEP Collider

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The Large Electron Positron collider LEP at CERN was commissioned in 1989 and finished operation in November 2000. During this period it was operated in different modes, with different optics, at different energies, and with varied performance. In the end, LEP surpassed all relevant design parameters. It has provided a large amount of data for the precision study of the standard model, first on the Z^0 resonance, and then above the $W^{\pm}$ pair threshold. Finally, with beam energies above 100 GeV, a tantalizing glimpse of what might have been the Higgs boson was observed. A brief history of the main modes of operation, associated performance, the highlights and the challenges met over the 12 years of running is presented.

1. INTRODUCTION

The three massive vector bosons, the neutral Z^0 and the charged $W^{\pm}$, were first observed at the SPS proton-antiproton collider in 1982 [1]. LEP was designed with the aim of studying these bosons and was conceived as a two stage machine. For Z^0 production a beam energy of around 45.625 GeV is required whereas for $W^{\pm}$ boson pair production a beam energy of over 80.5 GeV is needed. At the end of its operational life over 4 million Z^0 bosons and around 10,000 $W^{\pm}$ pairs had been collected by each of the four experiments. These data, together with a painstaking beam energy calibration program, allowed studies of the Standard Model to be made with unprecedented high precision. In addition a push in energy in the last years of LEP operation allowed the LEP discovery reach for the Standard Model Higgs boson to be pushed from 95 GeV/c^2 in 1998 to around 113 GeV/c^2 in 2000 [2,3]. This increase was the result both of the increase of beam energy and the higher than expected luminosity production at these higher beam energies.

LEP produced its first collisions on August 13th 1989, less than six years after ground was broken on September 13th 1983. Following the description in [4] we summarize the main features of LEP. The ring extended from the foothills of the Jura mountain to the Geneva airport and straddles the border between France and Switzerland. The 3.8 m diameter machine tunnel was buried at a depth varying between 50 and 175 m. The 26.65 km circumference LEP ring was composed of eight 2.9 km long arcs and eight straight sections extending for 210 m on either side of the 8 potential collision points, 4 of which housed the LEP experiments: L3, Aleph, Opal and Delphi. About 3400 dipole, 800 quadrupole, 500 sextupole and over 600 orbit corrector magnets were installed in the tunnel. The magnet lattice was of FODO type with a period (cell) length of 79 m and 31 regular lattice periods per octant. The bending angle per period was 22.62 mrad. The basic geometrical parameters of LEP are listed in Table 1. A detailed specification of LEP can be found in [5].

For LEP, the crucial factor in the definition of its circumference was the problem of synchrotron radiation wherein the transverse acceleration produced in circular accelerators leads to the emission of electro-magnetic radiation [6]. The amount of radiation is proportional to the fourth power of the particle energy and inversely proportional to the square of the bending radius in the dipoles ρ. The strong dependence of the radiation on the particle energy sets severe practical limitations on the maximum achievable energy of a circular lepton collider. First of all, the energy lost has to be replenished by a Radio Frequency (RF) system and secondly, the different hardware constituents of the collider have to be able to cope with power deposited by the synchrotron radiation. In LEP at 100 GeV, the radiated power for a total intensity of 6 mA was about 18 MW. At 104 GeV around 3% of the beam energy was lost to synchrotron radiation in one turn of the machine.

The power and cost of the RF system is defined to a large extent by the need to replace the energy lost by the particles due to synchrotron radiation. In LEP the RF system was installed in the straight sections around the 4 experiments and in the first instance copper cavities were installed for 45.6 GeV operations. This was followed by the staged installation of superconducting RF to allow the energy to be pushed to and beyond the W pair threshold. In the final year of operations the superconducting system consisted of 288 four-cell cavities operating at 352 MHz powered by 36 klystrons providing on average of 0.6 MW of RF power. This system was complemented by 56 cavities of the original copper RF system. A total accelerating voltage of 3630 MV was provided routinely allowing operation up to 104 GeV [7,8].

In the following sections, the performance of LEP is summarised, a short history of the 12 years of LEP operation is given, and then some important accelerator physics aspects are examined.

2. PERFORMANCE SUMMARY

The primary aim of LEP was the delivery of luminosity to the experiments and the key measure of success was the delivered integrated luminosity. Performance at LEP naturally divides into two regimes: 45.6 GeV running around the Z^0 boson resonance and high energy running above the threshold for $W^{\pm}$ pair production. A summary of the performance through the years is shown in Table 2.

The luminosity $\mathcal{L}$ of two colliding Gaussian beams (+ and -) may be expressed as [4]:

$$\mathcal{L} = \frac{N_{b+}\, N_{b-}\, f_{rev}\, k_b}{2\pi\sqrt{(\sigma_{x+}^2+\sigma_{x-}^2)(\sigma_{y+}^2+\sigma_{y-}^2)}} \cdot \exp\left\{-\frac{(\overline{x}_- - \overline{x}_+)^2}{2(\sigma_{x+}^2+\sigma_{x-}^2)} - \frac{(\overline{y}_- - \overline{y}_+)^2}{2(\sigma_{y+}^2+\sigma_{y-}^2)}\right\} . \quad (1)$$

where N_{b-} and N_{b+} are the number of electrons and positrons per bunch. k_b is the number of bunches per beam, $(\overline{x}_- - \overline{x}_+), (\overline{y}_- - \overline{y}_+)$ are the horizontal and vertical offsets between the centres of the electron and positron beams and σ_{x-}, σ_{x+}, σ_{y-}, and σ_{y+} are the r.m.s. horizontal and vertical beam dimensions of the electron and positron beams.

By inspection one can see that the luminosity depends on the bunch current N_b, the number of bunches k_b, the beam size σ_x, σ_y at the interaction point, and the beam-beam offsets $\overline{x}_- - \overline{x}_+$ and $\overline{y}_- - \overline{y}_+$. All of these factors were targeted in the search for increased performance. In the regime on or around the Z^0 resonance performance was constrained by the beam-beam effect (see below) which limited the bunch currents that could be collided. The beam-beam effect blew up beam sizes and the beam-beam tune shift saturated at around 0.04 for LEP1 [9]. Optimization of the transverse beam sizes was limited by beam-beam driven effects such as flip-flop. Operations was often unstable as the hard beam-beam limit was constantly probed. The main breakthrough in performance at this energy was an increase in the number of bunches: first with the Pretzel scheme (8 bunches a beam) commissioned in 1992 [10], and then with the bunch train scheme (up to 12 bunches per beam) used in 1995 [11]. Both schemes reduced the bunch current that was collided and also the resultant beam-beam tune shift. This was attributed to effects of parasitic long-range encounters. The increase in number of bunches, however, provided a net gain. The optics (phase advance and tunes values) were also changed in an attempt to optimize the emittance and the beam-beam behaviour.

With the increase in energy to above the $W^{\pm}$ threshold the beam-beam limit was raised and an important beam-based challenge was to develop a low emittance optics with sufficient dynamic aperture to go to the 100 GeV regime [12,13]. Luminosity production was maximized by increasing the bunch current to the limit while operating with four bunches per beam and rigourous optimization of vertical and horizontal beam sizes.

Between 1996 and 2000 the beam energy was progressively increased from 80.5 to 103 GeV. At these energies beam oscillations are strongly damped and the single particle motion has an important random walk component due to the large

Table 1
Geometric parameters of LEP.

Parameter	Symbol	Value
Effective bending radius	ρ	3026.42 m
Revolution frequency	$f_{\rm rev}$	11245.5 Hz
Length of circumference, $L = c/f_{\rm rev}$	L	26658.9 m
Geometric radius ($L/2\pi$)	R	4242.9 m
Radio frequency harmonic number	h	31320
Radio frequency of the RF-system, $f_{\rm RF} = h\, f_{\rm rev}$	$f_{\rm RF}$	352 209 188 Hz

Table 2
Overview of LEP performance from 1989 to 2000. $\int \mathcal{L}dt$ is the luminosity integrated per experiment over each year and I_{tot} is the total beam current $2k_{\rm b}I_{\rm b}$. The luminosity $\mathcal{L}$ is given in units of $10^{30}\rm cm^{-2}\ s^{-1}$.

Year	$\int \mathcal{L}dt$ (pb^{-1})	$E_{\rm b}$ (GeV/c^2)	$k_{\rm b}$	I_{tot} (mA)	$\mathcal{L}$
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5 - 86	4	4.2	35.6
1997	73.4	90 - 92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98 - 101	4	6.2	100
2000	233.4	102 - 104	4	5.2	60

number of emitted photons. Consequently particles no longer lock on higher-order resonances driven by the non-linear beam-beam force and beam size blow up is reduced allowing the use of higher bunch currents. Record beam-beam tune shifts of about 0.08 were achieved.

The actually achieved performances are compared to the LEP design parameters [5,14]. It is noted, that the design beam energy for LEP1 was 55 GeV, significantly above the operational LEP1 energy of around 45.6 GeV, as dictated by the Z-mass. The design parameters used here are taken from [5,14] and were not adjusted for this discrepancy, as the changes would be small [15]. The design and achieved values for a number of crucial LEP performance parameters are summarized in Table 3. It is seen that LEP clearly surpassed all design expectations. In particular the peak luminosity at LEP2 was almost a factor of 4 above design. The achieved emittance ratio was ten times smaller than expected.

The achieved instantaneous luminosity is shown in Figure 1 for each year of LEP operation. The design luminosities are indicated for both LEP1 and LEP2. It is seen that the LEP1 design luminosity was reached and surpassed in the fifth year at 45.6 GeV, exploiting the Pretzel scheme with an increased number of bunches per beam. Highest luminosity at 45.6 GeV was achieved with bunch train operation in the seventh year, when the LEP1 peak luminosity reached 210% of its design value. The highest LEP2 luminosities reached about 400% of the LEP2 design value. In the last year of LEP, peak luminosity was voluntarily reduced in order to maximize the beam energy [16–18].

The integrated luminosity that was delivered to the experiments was a function of the instantaneous (peak) luminosity and the accelerator efficiency. The efficiency in an accelerator is reduced due to the time required to diagnose and repair problems, to set-up luminosity conditions, to turn-around the fills (machine cycling, injection, ramping, setting up of collisions), etc. The LEP

Table 3
LEP: design and reality.

Parameter	Design (55/95 GeV)	Achieved (46/98 GeV)
Bunch Current	0.75 mA	1.00 mA
Total Beam Current	6.0 mA	8.4 mA/6.2 mA
Vertical Beam-beam parameter	0.03	0.045/0.083
Emittance ratio	4.0%	0.4%
Maximum Luminosity	16/27 $10^{30} cm^{-2} s^{-1}$	34/100 $10^{30} cm^{-2} s^{-1}$
Horizontal beta function at IP	1.75 m.	1.25 m.
Vertical beta function at IP	7.0 cm.	4.0 cm.

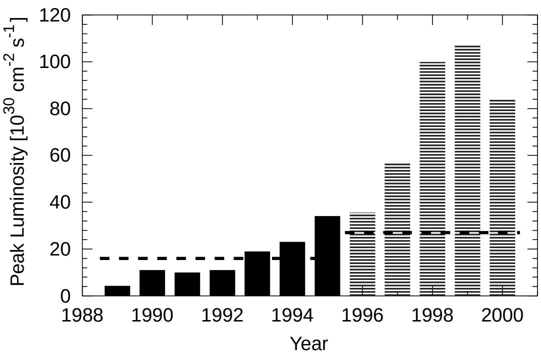

Figure 1. Peak luminosity achieved in each year of LEP operation. The dotted lines indicate the LEP1 and LEP2 design values.

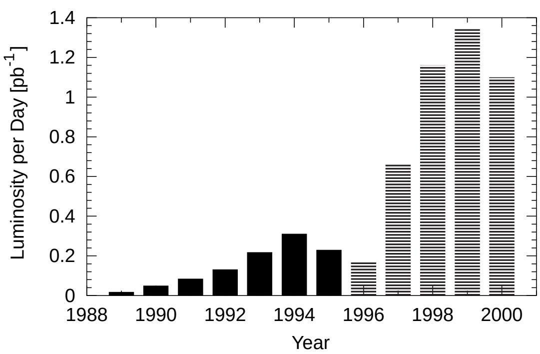

Figure 2. Luminosity delivered on average in one day of accelerator operation for each year of LEP running.

efficiency was constantly improved over the years: a thorough cold-checkout minimized the number of problems to be fixed with beam, a vertical realignment of all quadrupoles ensured faster set-up of nominal luminosity conditions, and the operational procedures were constantly improved for a faster set-up of luminosity runs. The importance of the improvements in accelerator efficiency is shown in Figure 2, where the average delivered luminosity per day is given for each year of LEP operation. From Figure 1 we see that there was no improvement in peak luminosity over the years 1990-1992. Nevertheless, improvements in the efficiency increased the luminosity production rate by a factor 2.6 during the same period. The production rate for Z physics in 1994 was 17 times larger than the one in 1989 and 6 times larger than in 1990.

3. OPERATIONAL HISTORY

3.1. Commissioning

Commissioning started on the 14th July 1989 with the first beam injected into the machine. By 23rd July circulating beam had been established and by 4th August a single beam had been taken to 45.6 GeV. The first colliding beams were established on the 13th August with the first Z boson

Table 4
Optics, main modes of operations and bunch scheme from 1989 to 2000.

Year	Optics	Comment	Bunch scheme
1989	60°/60°	LEP commissioned	4 on 4
1990	60°/60°		4 on 4
1991	60°/60°	90°/90° optics tested	4 on 4
1992	90°/90°	Pretzel commissioned	4 on 4 / Pretzel
1993	90°/60°		Pretzel
1994	90°/60°		Pretzel
1995	90°/60°	tests at 65-68 GeV	Bunch trains
1996	90°/60°	108°/90° tested	4 on 4
1997	90°/60°	108°/60° and 102°/90° tested	4 on 4
1998	102°/90°		4 on 4
1999	102°/90°		4 on 4
1999	101.5°/45°	High-energy polarization optics	Single beam
2000	102°/90°	Max. Energy 104.5 GeV	4 on 4

seen shortly after.

3.2. The early years

The first full year of operations was 1990 and life was a bit of a struggle. Total beam current was around 3 mA and peak luminosity $2 - 3 \cdot 10^{30} cm^{-2}s^{-1}$. The optics used had a 60°phase advance in both planes and beam sizes were revealed to be large. Worries reflected in the proceedings of the post run Chamonix meeting included: development of a new optics (still 60° but with different integer tunes), vertical dispersion, dynamic aperture, closed orbit, intensity limitations at injection, longitudinal oscillations and beam-beam. The Pretzel scheme, which was to increase the number of bunches to eight per beam, was already under consideration [10]. The struggles continued in 1991, when operations were wrestling with, among other things, the control system and beam losses in the ramp. Tests were made with the variant 60°/60° optics, the Pretzel scheme, and of an optics with a 90°degree phase advance. 1992 saw the introduction of a new suite of high-level software and an attempt to use a 90°/90° optics with a combined ramp and squeeze (in which the β_y squeeze is performed during the energy ramp, rather than after it). The start-up was an unmitigated disaster, with the conclusion being reached that the 90°/90° optics was unstable; the combined ramp and squeeze was abandoned. A switch back to the 60°/60° optics went somewhat more smoothly. Later in the year 90°/90° was tried again and worked. Pretzel was commissioned. A summary of different LEP optics used throughout the years is given in Table 4.

3.3. Z^0 production

By 1993 things had started to settle down, the control system was eventually taking shape, the optics was now 90°/60° and Pretzel was operational. During the 1992 to 1993 shutdowns there had been a major realignment of the machine and this had clearly helped to improve the performance. Design luminosity was reached and passed in the course of 1993. Luminosity production took place at a variety of energies as the Z^0 resonance was scanned. Bunch train machine development provided an interesting backdrop [11]. 1994 continued with Pretzel and 90°/60° and very respectable luminosity production, with beam-beam tune shifts of up to 0.047. Synchrotron injection was commissioned [19].

Bunch train tests continued and the search for a high-energy optics was started with a first look at 108°/60° being made. A high-energy optics was required because of the increase in horizontal emittance with energy: it was predicted that the 90°/60° optics would run out of dynamic aperture at high energy.

In 1995 bunch trains were commissioned for standard operation. The original plan was to collide trains of 4 bunches per train. Operationally this proved very difficult with beam break-up and parasitic beam-beam deflections limiting the intensities that could be accumulated and ramped. Eventually 3 bunches per train became operational. The injection energy was raised to 22 GeV to boost the bunch current limit. Maximum peak luminosity for the Z^0 was reached, surpassing the original design luminosity by 100%. The integrated luminosity, however, was low. Tests on potential high-energy optics (108°/60° and 108°/90°) continued. The first superconducting RF cavities had been installed and in November 1995 physics with 65 and 68 GeV beams was successfully delivered.

3.4. 1996: Transitional year

Two Heineken bottles left in the vacuum chamber made for an interesting but frustrating start-up. The main aims of the year were to establish the RF system, deliver a reasonable amount of luminosity above the W pair threshold and confirm the choice of high-energy optics. The year started with the 108°/60° high-energy candidate optics. However, attempts to do physics at 45.6 GeV (Z^0s were required by the experiments at the start of each year to calibrate their detectors) with this low emittance optics proved difficult. Aperture searches revealed nothing and giving way to what looked like low dynamic aperture, the switch back to 90°/60° was made. Things progressed smoothly and operations at a beam energy of 80.5 GeV, just above the W pair threshold, was established. At the end of the year there was an extended test with the 108°/90° optics, luminosity was produced but the performance was below that of the 90°/60° optics.

3.5. High energy running

Start-up 1997 was delayed by the recovery from a major fire in one of the surface buildings of the SPS. Nonetheless it was a reasonable year with the energy pushed to 91.5 GeV. With the high beam energies synchrotron radiation had started to cause problems with vacuum leaks, a major problem throughout the year. While operating with 90°/60°, 108°/90° investigations confirmed the large de-tuning expected from this optics and a possible explanation for the poor performance. In the mean time, a 102°/90° optics was developed [12] and a week long test with this at the end of the year was successful. The search for a high-energy optics was over. Staged installation of more superconducting cavities was taking place during the annual shutdowns and in 1998 the energy was pushed to 94.5 GeV. Dispersion-free steering [20] was introduced to simultaneously optimize orbit, dispersion, and corrector settings. Despite problems in the ramp caused by HOM heating of RF antennae cables, performance was excellent, with instantaneous luminosity of up to $10^{32}\text{cm}^{-2}\text{s}^{-1}$ and record beam-beam tune shifts of up to 0.075. This trend continued with another record year in 1999 with luminosity production at 98, 100 and 101 GeV and beam-beam tune shifts of up to 0.083. After 10 years the LEP team had finally mastered the machine and the main concern was continual, painstaking tuning and maintenance of the large superconducting RF system.

3.6. 2000: Pushing the limits

There was very little additional RF installed between 1999 and 2000, but there was the exhortation from the physics community to maximize the Higgs reach. This meant delivering a sizeable amount of luminosity at the maximum possible energy. A very concerted effort was made which included pushing the RF system to its limit, reducing the RF frequency (buying increased energy damping and thus effective RF voltage), using the orbit correctors as bending magnets [21], and an operational strategy which involved changing the energy of the beam during a physics fill. The different modes of running at 98 GeV (plenty of margin for trips of RF units), mainly 102.7 GeV (some margin for trips of RF units), and mainly 104.1 GeV (no margin) are illustrated in Figure 3. The result was a resounding success with luminosity delivered up to a maximum energy of 104.5 GeV. A total of 233 pb^{-1} was delivered of which 131 pb^{-1} was between 103 and 103.5 GeV, with 10.7 pb^{-1} over 104.0 GeV, this enabling the highest possible limits to be set in chargino searches [18]. The delivered luminosity allowed the limit on the Standard model Higgs mass to be pushed further than expected, and in June 2000 Aleph observed a high signal-to-background four jet Higgs candidate with a mass around 115 GeV/c^2. As the year progressed the strength of their signal at this mass continued to grow, and the excess reported by Aleph in September 2000 motivated the demand for a 2 month extension by the LEP experiments. In the end a total 6 weeks extension was granted, and subsequently Higgs candidates were also seen by other experiments in other channels. A combined excess of 2.9 σ with respect to the background hypothesis was reported at the end of the 2000 run. A very vocal request to run in 2001 provided management with a keen dilemma, squeezed as CERN was by the tight LHC schedule. The decision to close LEP for good was announced on the 8th November.

4. INTENSITY LIMITATIONS

The bunch currents that could be collided at 45.6 GeV were limited by beam-beam effects. However, the experienced increase in the beam-beam limit at high energy was anticipated and a lot of effort was made to push the bunch current limit at injection. In the end, however, the bunch current was limited operationally by the stability of the RF system.

The fundamental intensity limit at LEP was the transverse mode coupling instability (TMCI) wherein the low lying head-tail oscillation modes of an individual bunch are pushed together with increasing intensity. The threshold of the instability is reached when the two modes have the same frequency [4]. Efforts to raise the threshold for the TMCI were made: the injection energy was increased from 20 to 22 GeV, transverse impedance was reduced with the removal

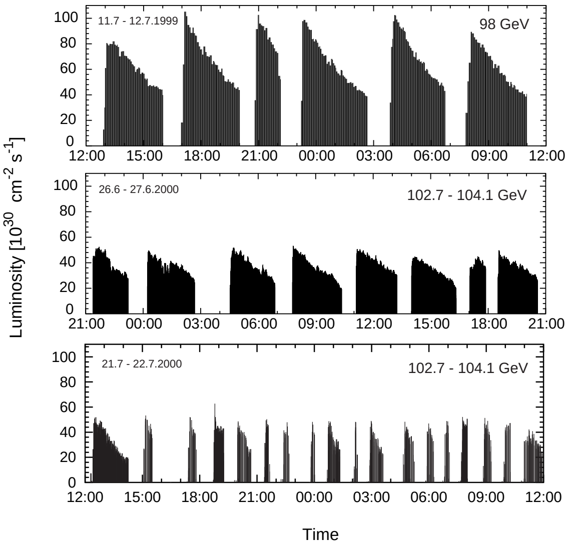

Figure 3. Instantaneous luminosity versus time for three different running modes of LEP (stable 98 GeV running, running mainly at 102.7 GeV, and running mainly at 104.1 GeV).

of copper RF cavities, the synchrotron tune was increased from 0.08 (design value) to 0.13. The decrease in bunch length that accompanies the latter was compensated by the use of wigglers. With these improvements the bunch current was taken to the TMCI limit [22] of around 1 mA per bunch during machine development.

5. BEAM-BEAM

Associated with each bunch is a strong non-linear electro-magnetic field which deflects individual particles of the counter-rotating beam at each collision [23]. For small displacements from the center of the bunch this field varies linearly with distance, as for a normal quadrupolar lens, whereas at larger displacements the field is highly non-linear. The non-linearity of the beam-beam force causes beam size blow-up and drives higher-order resonances.

The importance of the beam-beam interaction as a performance limitation to circular electron-positron colliders was well established before the construction of LEP [23]. A purely analytical treatment of the beam-beam interaction is difficult due to the complexity of the forces and the high number of particles involved. Simulation techniques had gained in importance with the development of detailed codes and the availability of more powerful computers. These studies strongly influenced the design of LEP, namely: the symmetry between the four interaction regions, the choice of the optics, the tune working point and the installation of wiggler magnets [24–26].

The beam-beam force produces a tune spread which is related to the beam-beam strength parameter. For flat beams ($\sigma_{\rm y} \ll \sigma_{\rm x}$) the beam-beam parameters are in a good approximation given by:

$$\xi_{\rm x} = \frac{r_{\rm e}}{2\pi\,\gamma}\,\frac{N_{\rm b}\,\beta^*_{\rm x}}{\sigma^2_{\rm x}} = \frac{r_{\rm e}}{2\pi\,\gamma}\,\frac{N_{\rm b}}{\epsilon_{\rm x}} \quad (2)$$

$$\xi_{\rm y} = \frac{r_{\rm e}}{2\pi\,\gamma}\,\frac{N_{\rm b}\,\beta^*_{\rm y}}{\sigma_{\rm x}\sigma_{\rm y}}\ . \quad (3)$$

As noted above, LEP operated in two regimes: the first, on the Z^0 resonance at around 45.6 GeV was well into the soft beam-beam limit and approaching the hard limit [27], the second was at high energy where strong damping lifted the beam-beam limit and LEP was not beam-beam limited. There was unique experience with ultra-strong damping at LEP with high energy providing a very good operating regime. Extremely strong transverse damping (60 turns at 104 GeV) meant that the second beam-beam limit was avoided as the beam-beam limit was pushed upwards. The beam-beam performance is summarized in Table 5. Operationally, LEP profited from smaller vertical emittances and higher currents. The 1/3 resonance could be jumped to a more favorable working point, and it was possible to ramp the beams in collision with collimators closed. By looking at the functional dependence of beam-beam parameter on bunch current, attempts were made to infer the beam-beam limit at high energy. Although the beam-beam limit was not reached, some beam blow up was observed. Figure 4 shows the vertical emittance versus bunch current, as calculated from the luminosity and as measured through the BEXE beam size measurement [28,29].

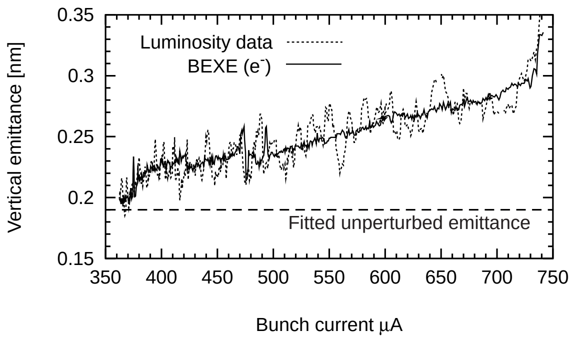

Figure 4. Vertical emittance versus bunch current for a given fill. The emittance calculated from the luminosity and the BEXE vertical beam size measurement agree well and are consistent with the fitted zero-current emittance.

Based on a stochastic model of the beam-beam interaction the following relation between the beam-beam parameter and the bunch current was derived [30]:

$$\xi_{\rm y} = \sqrt{\frac{1}{A + (B \cdot i_b)^2}} \cdot i_b\ . \quad (4)$$

Here, i_b denotes the bunch current. The parameter A is given by the known machine parameters and the zero current emittances ϵ^0_x and ϵ^0_y:

$$A = \left(\frac{2\pi e f_{rev}\gamma}{r_e}\right)^2 \cdot \frac{\beta^*_{\rm x}}{\beta^*_{\rm y}} \cdot \epsilon^0_x \cdot \epsilon^0_y\ . \quad (5)$$

The parameter B is a measure of the asymptotic beam-beam limit ξ^∞_y:

$$B = \frac{1}{\xi^\infty_y}\ . \quad (6)$$

The Equation 4 was fitted to experimental data. Figure 5 shows the data and fitted relationship for the physics fill with highest beam-beam parameter. The fit suggested a zero-current emittance

Table 5
Maximum vertical beam-beam parameter ξ_y, IP beta functions β_x^*/β_y^*, bunch current i_b, horizontal damping partition number J_x, and transverse damping time $\tau_{\rm transv}$ (in number of turns) for different beam energies.

Energy [GeV]	ξ_y per IP	β_x^*/β_y^* [m]	i_b [μA]	J_x	$\tau_{\rm transv}$ [T_0]
45.6	0.045	2.00/0.05	320	1.0	721
65.0	0.050	2.00/0.05	400	1.0	249
91.5	0.055	1.50/0.05	650	1.6	89
94.5	0.075	1.25/0.05	750	1.8	81
98.0	0.083	1.50/0.05	800	1.6	73
101.0	0.073	1.50/0.05	700	1.3	66
102.7	0.055	1.50/0.05	650	1.1	63

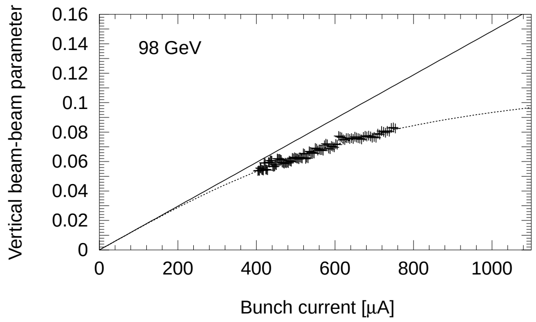

Figure 5. Vertical beam-beam parameter at 98 GeV versus bunch current.

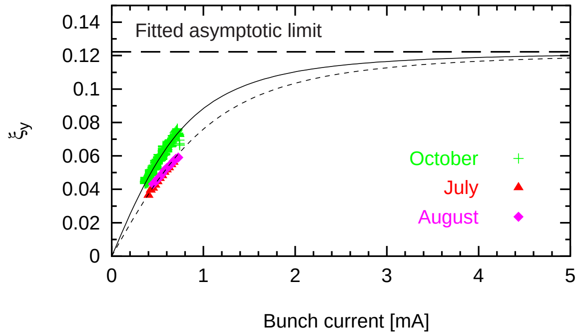

Figure 6. Vertical beam-beam parameter at 94.5 GeV versus bunch current, averaged over many fills and for three different periods in time. The observations are consistent with different vertical emittances and the same beam-beam limit.

of 0.11 nm and an asymptotic beam-beam limit of 0.115. Figure 6 illustrates the results of fits to data from July, August, and October 1998. The data sets are compatible with a beam-beam limit of 0.12 and zero-current emittances of 0.19 nm in October and 0.27 nm in July and August. We see from Figure 4 that the fitted zero-current emittance was consistent with the measured vertical beam size.

The LEP data consistently suggested a beam-beam limit around 0.115 for many different fills at around 94.5 to 98 GeV. Given the data at different energies a scaling law [31] relating the damping decrement $\lambda_d = 1/(f_{rev} \cdot \tau \cdot n_{ip})$ with the beam-beam limit ξ_y^∞ could be obtained [30]:

$$\xi_y^\infty \propto (\lambda_d)^{0.4} \qquad (7)$$

Note that the LEP data was obtained with four interaction points ($n_{ip} = 4$), covering a wide range of different transverse damping times τ (63 to 721 turns).

6. LUMINOSITY OPTIMIZATION

The achievement of high LEP luminosities required the careful set-up and continual optimization of the accelerator. During start-up, the optics had to be carefully tuned. The tunes, coupling, chromaticity, orbit and dispersion were carefully corrected, the beta functions were measured and adjusted. Collisions were established and the beam-beam offset was minimized using electro-static bumps [32,28].

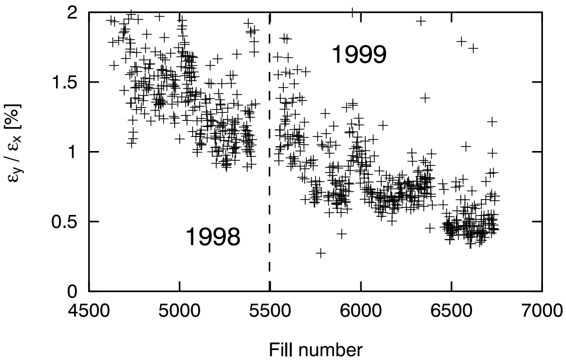

Figure 7. Evolvement of the emittance ratio during 1998 and 1999.

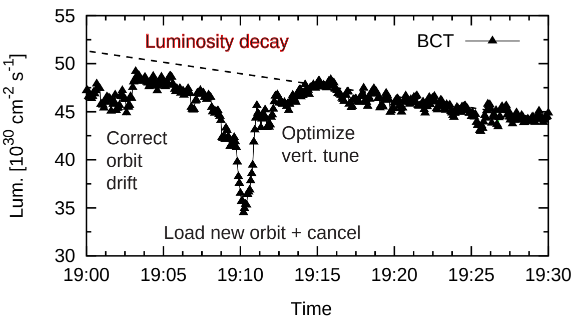

Figure 8. Example of empirical luminosity tuning in LEP.

Once collisions were established, maximising luminosity required continual optimization. The efforts for LEP1 concentrated on running as close as possible to the beam-beam limit. Wigglers were used to blow-up the beam sizes at start of physics. As the current decayed the wigglers were gradually ramped down in order to remain at the beam-beam limit. The tunes, orbit, and other variables were continually optimized for lowest background and highest luminosity.

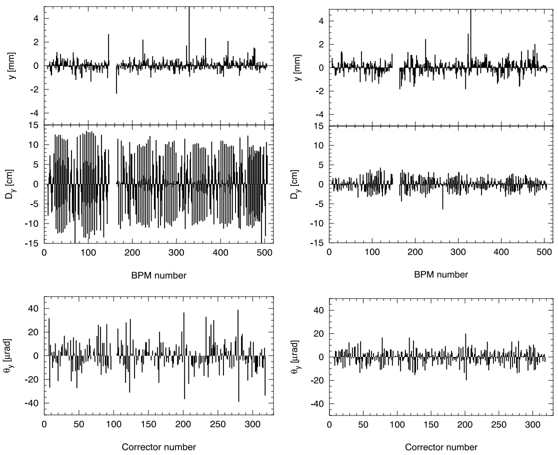

Figure 9. Example of dispersion-free steering for a single beam. Vertical orbit (top), vertical dispersion (middle), and corrector settings (bottom), before (left) and after (right) dispersion-free steering.

The situation at LEP2 was qualitatively different. The strong radiation damping left the beams very stable with no observable beam tails. The beam-beam limit was not reached. As the horizontal spot size was mainly given by design horizontal dispersion and the energy spread, the instantaneous luminosity was optimized by reducing the vertical beam size. Figure 7 illustrates the history of the emittance ratio in LEP during 1998 and 1999. It is seen that the emittance ratio was significantly reduced, even while the energy and the horizontal spot size were pushed up.

At high energy, after careful coupling correction, the vertical spot size was essentially limited by the vertical dispersion. Optimization was initially performed in an empirical way, optimizing the vertical orbit, the vertical dispersion, and the tunes on a trial and error base. Different changes were tried, keeping only the beneficial manipulations. An example of empirical tuning is shown in Figure 8. The empirical tuning was later complemented with a deterministic optimization of the vertical dispersion. An example of the so-called "dispersion-free steering" [20] is shown in Figure 9. The vertical rms dispersion was reduced from typically 3.5 cm to 1.5 cm, resulting in an important reduction in the vertical emittance. The vertical emittance at LEP was so highly optimized that it became susceptive to drifts of the vertical orbit on the 20 μm r.m.s. level.

7. POLARIZED BEAMS AND ENERGY CALIBRATION

The "physics reach" of LEP was strongly enhanced by the precise calibration of the beam energy, relying on polarized beams. The spin dynamics of LEP is described in detail in [33]. The lepton beams in LEP self-polarized due to the Sokolov-Ternov effect [34]. The spin polarization builds up in the vertical transverse direction and (without imperfections) reaches an asymptotic degree P of 92.4%. The exponential build-up time τ_p of radiative polarization is a function of the bending radius in the storage ring and the beam energy. For LEP at 100 GeV it was as small as 6 minutes, to be compared to 5.7 hours at 45 GeV.

Depolarization is caused by unavoidable imperfections in the vertical orbit of planar storage rings and is enhanced by synchrotron radiation. It is characterized by a depolarization time τ_d. The asymptotic degree P of polarization is reduced to:

$$P = \frac{92.4\%}{1 + \tau_p/\tau_d} . \quad (8)$$

The LEP beams allowed the study of the behaviour of polarization in a unique range of high beam energies. Measurements at LEP and other lepton storage rings are summarized in Figure 10. It is seen that the measurements at LEP cover a range from about 40 to 100 GeV, inaccessible to other storage rings. The LEP polarization benefited from advanced Spin Matching techniques [35,36], as illustrated in Figure 11.

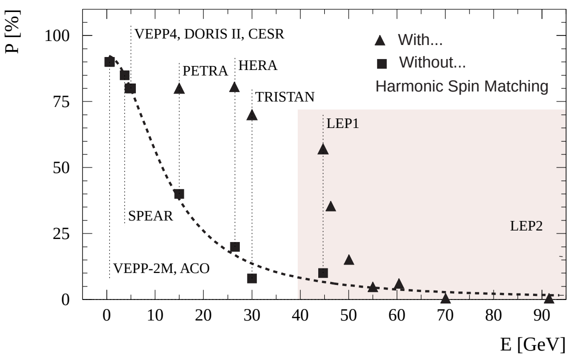

Figure 10. Maximum observed levels of polarization versus beam energy for different electron storage rings. The polarization level is indicated with (triangle) and without (square) Harmonic Spin Matching.

The maximum observed levels of transverse polarization in LEP are shown in Figure 12 for different beam energies. The measurement at 44.7 GeV is extrapolated to higher beam energies using a theory for depolarization at ultra-high energies by Derbenev and Kondratenko [37], assuming the same residual imperfections in the vertical orbit. The experimentally observed sharp drop in radiative spin polarization at LEP is in good agreement with the behavior expected from polarization theory. Measurements between 44.7 GeV and 60.6 GeV are below the expectation because they were not fully optimized. The LEP measurements are the first experimental confirmation of the theory that Derbenev and Kontratenko developed in the 1970s.

Spin precession is described by the Thomas-BMT equation [38]. For LEP, the classical "spin vectors" of particles precess around the vertical direction with a frequency f_{spin} that is ν times the revolution frequency f_{rev}. The number ν is

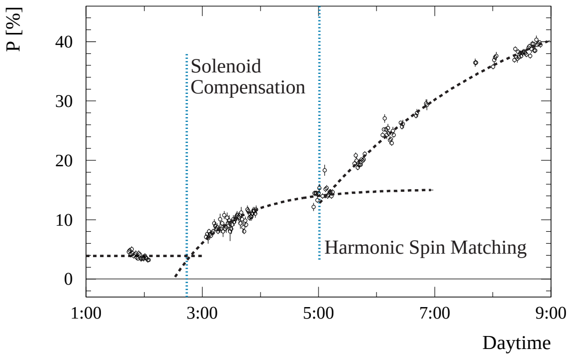

Figure 11. Measured polarization versus time, showing the beneficial effects of solenoid spin matching and deterministic harmonic spin matching. This measurement was done parasitic to energy calibration on other bunches, explaining the missing measurements.

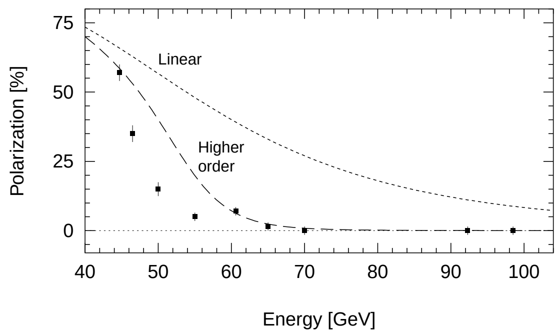

Figure 12. Maximum polarization values observed at LEP, versus beam energy. The measurements are compared with predictions from linear and higher-order theory.

called the spin tune and can be expressed as a simple function of the beam energy E:

$$\nu = \frac{E\ [\mathrm{MeV}]}{440.6486\ \mathrm{MeV}}\ . \tag{9}$$

Precise energy calibration by resonant depolarization of a polarized beam [39] relies on this simple relationship. If an external RF dipole field is applied in phase with the spin precession frequency, the "spin vectors" are resonantly rotated away from the vertical direction and the beam is depolarized. This method exhibits an extraordinarily high precision. Figure 13 shows the response of polarization to an external field with different frequencies. The average spin tune (average beam energy) of the beam was determined with an absolute accuracy of about 0.2 MeV, or about $5 \cdot 10^{-6}$ in relative terms [39].

The challenge of LEP energy calibration lay in understanding the factors that affected the beam energy, developing a model and then using this model and magnet measurements to extrapolate between the infrequent resonant depolarization measurements. Important systematic effects on beam energy were identified: the tides of Lake Geneva, electrical currents from the French high speed train TGV, and last but not least the earth tides. As the earth is deformed by the gravitational forces of Earth and Sun, the LEP diameter of 27 km is changed by a few mm with a period of 12 hours. As the particles in LEP travel with almost light velocity, their speed is constant for practical purposes. Synchronisation with the RF frequency means that the length of the LEP orbit must then stay the same and the equilibrium beam energy must adjust itself accordingly. The measured change of the beam energy due to the earth tides is shown in Figure 14 for three different days. It is seen that the observed LEP energy variation is in full agreement with the prediction from a geophysical calculation. This allowed precise interpolations between direct energy measurements.

Best possible estimates of the energies over 15 minutes intervals were given to the LEP experiments for data analysis. The final result was a systematic error due to the energy calibration of the LEP beams of 1.7 MeV on the mass, and of 1.3 MeV on the resonance width, of the Z^0 boson [40]. At LEP2 a direct energy calibration by resonant depolarization was not possible because transverse polarization was suppressed at such high energies (see Figure 12). The beam energy is

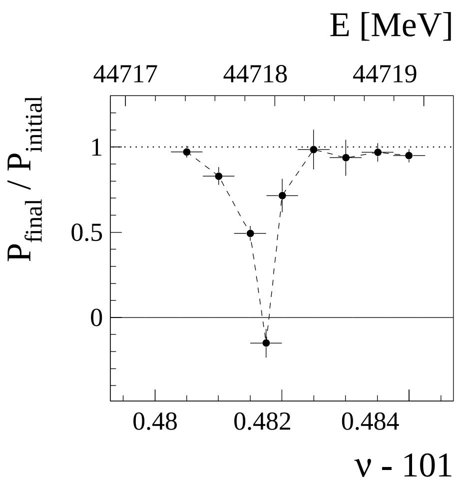

Figure 13. Width of the depolarizing resonance excited for energy calibration at LEP.

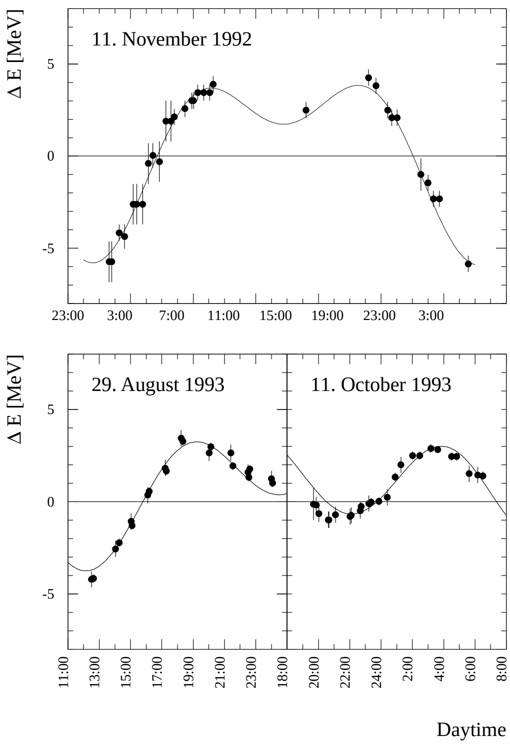

Figure 14. Measured variation of the LEP beam energy versus time, for three different days. The measurements are compared to the predicted change due to earth tides.

established by extrapolation from measurements performed at lower energies, cross-calibrated with measurements from NMR probes installed in the dipoles, and NMR measurements made at physics energy.

8. RF

The move to center-of-mass energies above the W pair threshold was originally foreseen in the original LEP design proposals. A program of research and development into the use superconducting RF technology was initiated. This was not without challenges, but eventually the program led to industrial production. Staged installation from 1995 to 1999 allowed a corresponding increase of the beam energy [7,8]. The evolvement of nominal RF voltage (assuming design gradient of 6 MV/m), available RF voltage, and beam energy is summarised in Figure 15. The last superconducting modules were installed in the shutdown between 1999 and 2000. The modules ended up performing at field gradients well above nominal and, together with some operational tricks, allowed the beam energy to be pushed to 104.4 GeV, well above even the most optimistic estimates. The final complement of superconducting RF was 288 cavities driven by 36 klystrons. In the final year of LEP operations the RF system consistently delivered a total voltage around 3650 MV [7,8].

9. CONCLUSION

Challenges were ever present at LEP, from commissioning, the choice of optics, the introduction of ambitious multi-bunch schemes, continual optimisation and the use of polarized beams for energy calibration. The move to high energies

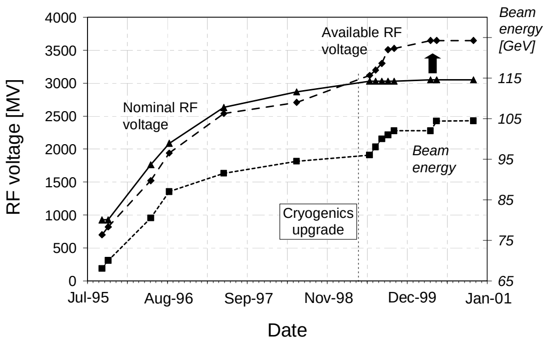

Figure 15. The nominal RF voltage (assuming the design gradient of 6 MV/m), the actually available RF voltage, and the LEP beam energy versus time.

involved more new optics, the technological challenges of the superconducting RF system and the effort required to keep the whole system running at way above design, the problems of intense synchrotron radiation and the pleasures of moving into the ultra strong damping regime where high bunch currents could be collided with impunity. By the end LEP had significantly surpassed all design expectations. It delivered over 200 pb^{-1} on the Z^0 resonance and almost 800 pb^{-1} over the $W^{\pm}$ pair threshold. This corresponds to over four million Z^0 bosons and around ten thousand $W^{\pm}$ boson pairs per experiment. The precision of the LEP beam energy was reduced by more than one order of magnitude with respect to original estimates using resonant depolarization, yielding some of the most precise measurements in accelerator physics. The data produced at LEP allowed the Standard Model to be tested with unprecedented precision.

10. ACKNOWLEDGEMENTS

The 12 years of LEP represent a truly remarkable effort on behalf of all involved. The achievements reported in this paper are the direct result of the commitment, dedication, and ingenuity of the LEP team in all aspects of the design, the construction, the operation, and the optimisation of LEP.

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