LEP OPERATION AND PERFORMANCE WITH ELECTRON-POSITRON COLLISIONS AT 209 GEV

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Abstract

The Large Electron-Positron Collider (LEP) at CERN completed its operation in 2000. Electron-positron collisions were established at centre-of-mass energies of up to 209 GeV. The maximum energy reach of LEP collisions was thus extended by another 7 GeV, compared to the year 1999. At the same time the luminosity rate was kept high, yielding a total delivered luminosity of 233 pb^{-1} in 2000. High beam energy and high luminosity allowed for an extended discovery reach of LEP. The successful energy increase of LEP is analysed in detail and the operation and performance in the regime of ultra-strong damping is described.

1 INTRODUCTION

Based on the collider performance (luminosity and energy), the Higgs 3 σ sensitivity for LEP can be calculated (assuming the standard model cross sections) [1]. It is shown in Figure 1 for the years 1998 to 2000. Given the delivered LEP luminosity and energy at a specific date, Figure 1 shows the largest Higgs mass that would have been observable from the LEP data with a statistical significance of 3 standard deviations. The LEP discovery reach for the Higgs boson was pushed from 95 GeV/c^2 to 113 GeV/c^2 from 1998 to 2000. This increase in discovery reach was the result both of the successful increase of beam energy and the higher than expected luminosity production at the LEP2 beam energies. In this paper the different contributions are analysed.

Table 1 summarises the maximum beam energies, integrated luminosities and the average rate of luminosity production for 1994 to 2000. Figure 2 shows the LEP luminosity production versus time for the years 1989 to 2000. The LEP performance was improved significantly over the years. From the totally delivered 1000 pb^{-1} per experiment (from 1989 to 2000) almost 70 % were produced in the last three years. The distribution of delivered luminosity versus beam energy is shown in Figure 3 for the year 2000.

2 ENERGY REACH OF LEP

The LEP collider was the highest energy electron-positron colliders to date. Its energy surpassed that of other e+e- colliders by more than a factor of three. The achievable beam energy in a storage ring is in principle determined by several factors:

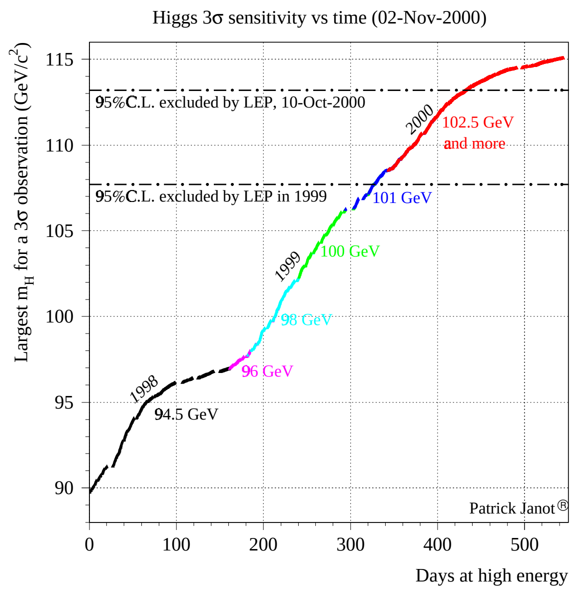

Figure 1: Given the delivered luminosity and energy at a specific date, the largest standard model Higgs mass, as observable from the LEP data with a statistical significance of 3 standard deviations, is shown.*

Table 1: Overview of LEP performance 1994-2000.

Year	Beam energy [GeV]	Total luminosity [pb^{-1}]	Average luminosity rate [pb^{-1}/day]
1994	45.6	64	0.31
1995	45.6 – 70.0	47	0.23
1996	80.5 – 86.0	25	0.17
1997	91.0 – 92.0	75	0.66
1998	94.5	200	1.16
1999	96.0 – 101.0	254	1.35
2000	100.0 – 104.5	233	1.10

1. The achievable **field strength of the magnetic elements** that guide the beam in a circle and provide the necessary transverse beam stability. The required field scales linearly with beam energy.
2. The available **accelerating field** that compensates radiative energy losses and provides the required longitudinal beam stability. In electron-positron

* Figure provided by P. Janot.

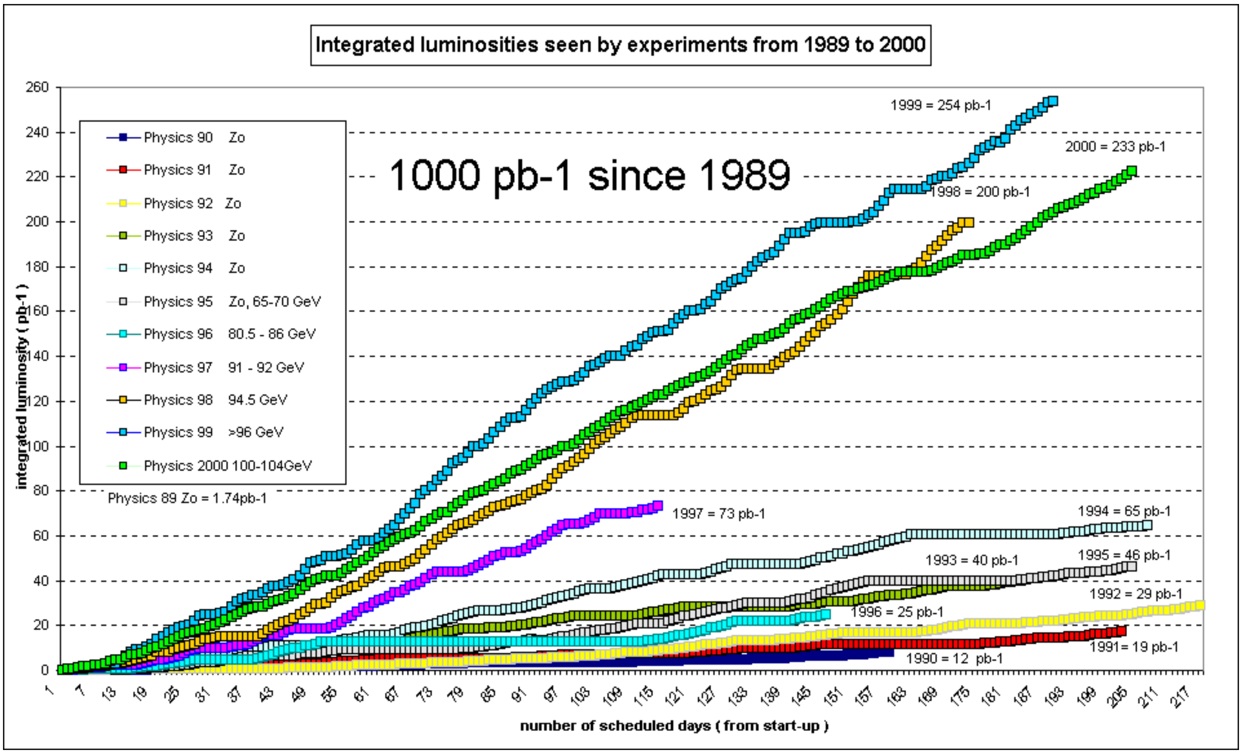

Figure 2: Luminosity production (per experiment) versus time for LEP. Separate lines represent the different years of operation; the corresponding beam energies are indicated in the labels. Almost 70 % of the total luminosity were produced in the last three years.

colliders the radiative energy loss per turn U_0 is a steep function of the beam energy E:

$$U_0\,[\mathrm{eV}] \approx 8.85 \cdot 10^4 \,\frac{E^4\,[\mathrm{GeV}]}{\rho\,[\mathrm{m}]} \qquad (1)$$

Here, an iso-magnetic lattice is assumed and ρ denotes the average bending radius of the ring collider (3100 m for LEP). In LEP at 104 GeV about 3% of the beam energy were lost per turn [2]. The accelerating field must replace the lost energy and provide sufficient overhead for longitudinal beam stability (about 14% over-voltage was required for LEP at 104 GeV).

3. Limits in the **dynamical behaviour** of the stored particle beams (dynamic aperture, transverse beam size, …).
4. **Legal limits**, for example due to the allowable level of radiation.

The legal limit of the beam energy for LEP was raised from 100.0 GeV to 105.0 GeV by the French authorities in summer 1999. For the start-up in 2000, the 102/90 optics [3] was optimised such that the available magnet field strength was sufficient for a beam energy of at least 105.0 GeV. It was also checked that the beam behaviour was acceptable for luminosity running at 105.0 GeV. In particular the 102/90 optics was modified to reduce the horizontal beam sizes in points 4 and 8.

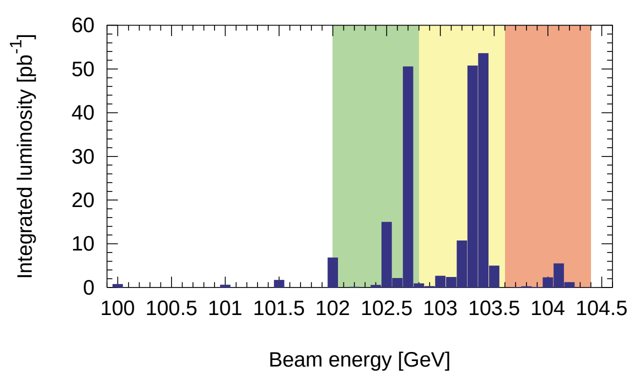

Figure 3: Distribution of delivered LEP luminosity in the year 2000 versus beam energy. The three bands of luminosity production correspond to the three typical beam energies during a single physics fill. The beam energy was ramped with colliding beams to move from one band to the next (compare section 2.5).

The available accelerating field, as produced by the RF system, then limited the **maximum beam energy** in LEP. Note that the maximum energy reach was also slightly increased with a larger average bending radius of the LEP closed orbit, as explained in section 2.4.

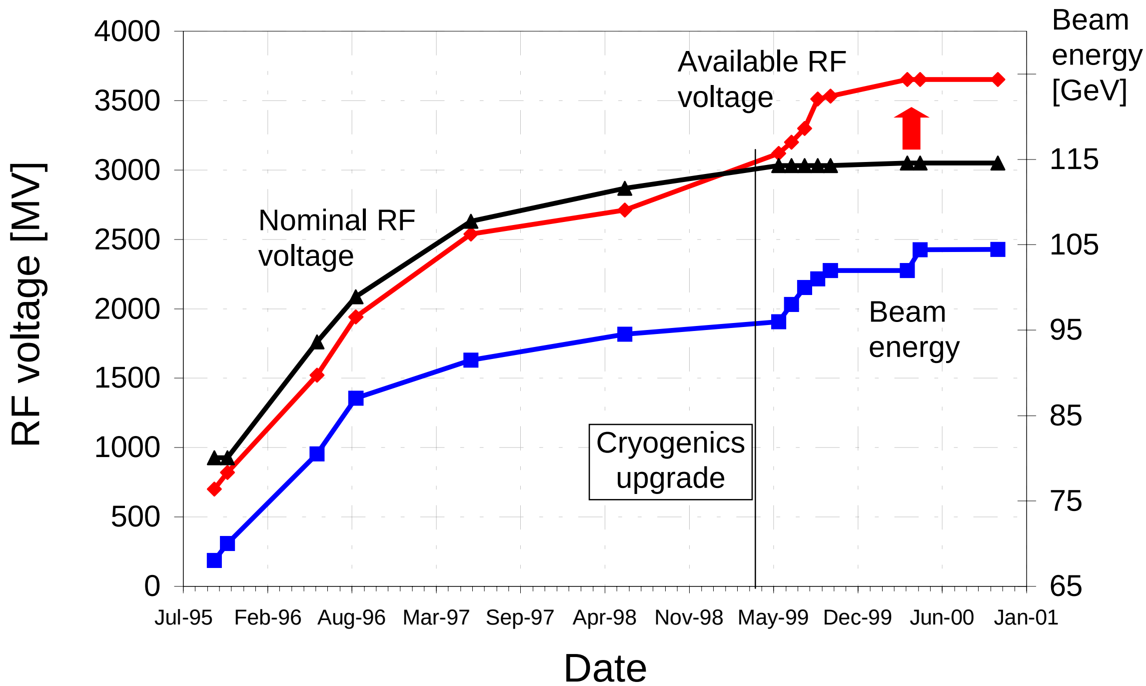

Figure 4: Evolution of beam energy, nominal voltage (with design gradient 6 MV/m) and available RF voltage.*

Table 2: Contributions to the energy increase in 2000. The different improvements are explained in the text.

Contribution	**Change in**	
	maximum energy	**effective energy**
Additional RF cavities	+0.14 GeV	
Higher RF gradient	+0.96 GeV	
Less RF margin		+1.60 GeV
Less RF frequency shift		+0.70 GeV
Increased bending radius	+0.17 GeV	
Total	**+1.27 GeV**	**+2.30 GeV**

To achieve a good efficiency of the collider, the effective **beam energy** for luminosity production is always set below the maximum energy (before the year 2000 it was typically lower by 1.6 GeV). The required "safety margin" is a function of the trip-rate of klystrons in the RF-system.

The discovery reach of LEP for the Higgs-boson was optimised by both pushing the maximum and effective beam energy:

1. Increase of the maximum achievable beam energy, mainly by increasing the total available accelerating field.
2. Increase of the effective energy of luminosity production (as close as possible to the maximum beam energy), mainly by reducing trip rate and safety margin and by optimising operational procedures.

The different contributions to the energy increase of LEP in the year 2000 are listed in Table 2. They are explained in the following sub-sections.

2.1 Available accelerating RF voltage

The evolution of the available RF voltage in LEP is shown in Figure 4 for the years 1995 to 2000. The RF voltage was increased in two ways:

1. **Installation of additional RF cavities**. It was in practise limited by the available space, infrastructure and resources. The resulting voltage increase is shown with the graph of "nominal RF voltage" (assuming the design gradient of 6 MV/m) in Figure 4. Most of the energy gain for LEP2 was due to the higher nominal RF voltage.
2. **Increase of the accelerating gradient** of the super-conducting RF cavities. Up to 1998 the accelerating gradient in the super-conducting Nb/Cu cavities was close to its design value of 6 MV/m. After a cryogenics upgrade, it was continually improved to a maximum value of 7.5 MV/m in 2000 (compare Table 3). As a result the available RF voltage in LEP was significantly higher than the nominal RF voltage in 1999 and 2000.

It should be noted that the RF system experienced significant damage during operation at high energies. An example of a less severe damage in a RF waveguide is shown in Figure 5. On one occasion a hole was melted into one waveguide, requiring its replacement.

* Data provided by O. Brunner.

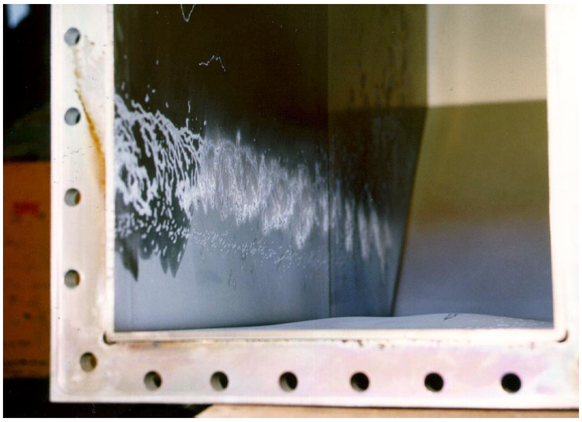

Figure 5: Damage in one of the LEP waveguides.

A few single cavities deteriorated during high energy operation and would not hold their previous high gradients. They had to be detuned permanently. The resulting slow degradation of the available RF voltage was absorbed by gradual increases of the accelerating gradients in other cavities.

2.2 Rate of RF trips

The RF system for LEP was the largest RF system in a storage ring to date. As shown in Figure 4, it was installed progressively and reached its largest potential in the year 2000. At the end of LEP it contained:

- 288 super-conducting cavities that were supplied by 36 klystrons plus the required waveguides.
- 53 kW cooling power of He at 4.5K, distributed to the 288 super-conducting cavities located in four different LEP insertions.
- 56 copper cavities that were supplied by 8 klystrons plus the required waveguides.
- About 10,000 interlocks for hardware protection.

The operation of the RF system could be disrupted to a certain extent by each of the 10,000 interlocks. Interlocks could disrupt one klystron, 2 klystrons or the beam. Trips occurred mainly on a statistical basis, most often produced by field emission, causing Helium level or pressure problems. The recovery of a tripped klystron usually took 2-3 minutes.

The temporary loss of a klystron caused a reduction of about 100 MV in the available accelerating RF voltage. During the time of the trip, the maximum LEP beam energy was then reduced by about 0.8 GeV. If at the time of the trip the beam energy was above the now reduced maximum energy, the beams were lost and physics ended. As a consequence, the beam energy should be 0.8 GeV below the maximum beam energy (all klystrons on) in order to have the beams survive a single RF trip and 1.6 GeV below the maximum beam energy to survive a double RF trip.

Table 3: Average accelerating field in the Nb/Cu cavities of LEP achieved at different beam energies. The design value is 6 MV/m.

Beam energy (year)	**Average accelerating field [MV/m]**
96 GeV (1999)	6.1
100 GeV (1999)	6.9
104 GeV (2000)	7.5

Table 4: Effective beam energy and average length of LEP physics fills, assuming constant energy, a voltage reduction of 100 MV per trip, a trip rate of 1/(14 minutes), and a recovery time of 2 minutes for the tripped klystron.

Effective beam energy	**Average length of physics fill**
Maximum	14 min
Maximum – 0.8 GeV	~ 1.5 hours
Maximum – 1.6 GeV	Set by dump

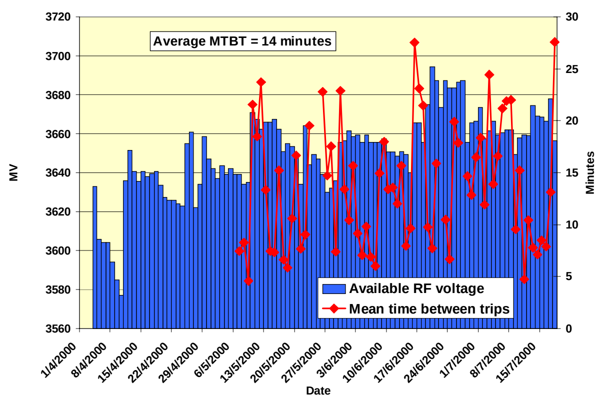

Figure 6: Available RF voltage (left vertical scale) and mean time between trips (right vertical scale) in LEP versus time (April to July 2000).*

The rate of RF trips determined the required overhead in RF voltage. As the trip rate depends on beam current the intensity at highest energies was operationally limited, also minimising transient voltage reductions during trips.

The RF stability was improved using fast GPS based diagnostics, active damping of field oscillations and various hardware improvements. Figure 6 shows the mean time between trips. It was about 14 minutes in 2000. The recovery time per trip was about 2-3 minutes.

The rate of one trip every 14 minutes illustrates the low efficiency when running at the maximum beam energy. The average length of physics fills would only be 14 minutes and short against the time required to re-establish physics (about 60 minutes). The probability to

* Figure provided by A. Butterworth.

experience another trip, during the 2 minutes recovery time of a tripped klystron, is about 1:7. Running at a beam energy that allows one klystron to be off, we do then calculate an average physics length of about 1.5 hours. This estimate is in excellent agreement with the experience in the 2000 run. Table 5 summarises the average length of physics fills, assuming a constant beam energy in each fill. The trade-off between beam energy and efficiency is evident.

2.3 Horizontal damping partition number

The horizontal beam size σ_x is proportional to beam energy E, the rms horizontal dispersion D_x^{rms}, the betatron function β_x and the horizontal damping partition number J_x:

$$\sigma_x \propto \sqrt{\beta_x / J_x} \cdot D_x^{rms} \cdot E \qquad (2)$$

The increase of horizontal beam size with energy results in lower luminosity and larger background in the experiments. This is counteracted with a high Q_x optics [3] and an operational increase of J_x through an increase of the RF frequency. However, the increased J_x reduces both beam energy (longer orbit) and RF voltage overhead (larger energy spread) [4]. For maximum LEP beam energy it was desirable to run with the largest σ_x (lowest J_x) possible.

When enough margin in RF voltage was available (for example at lower beam energy) it was advantageous to run with large positive RF frequency shifts (high J_x). The RF frequency shift and J_x were controlled automatically for LEP. A specific computer program was monitoring the beam energy and the available RF voltage. Its display is shown in Figure 7 for three different cases:

1. The trip of one klystron reduces the RF voltage by 94 MV.
2. The tripped klystron is recovering, providing already 20 MV.
3. All klystrons are working normal with a total voltage of 3641 MV.

The computer program computed the available margin in RF voltage from the actual beam energy and RF voltage and set the RF frequency shift and J_x accordingly. Figure 8 shows an example of the RF frequency shift Δf_{RF} (with respect to the central frequency) versus time. The data illustrates the automatic control of Δf_{RF} and J_x. The J_x was increased to about 1.6 (Δf_{RF} = + 102 Hz) for maximum luminosity at lower beam energies, where sufficient voltage margin was available. In the case of a RF trip and subsequently reduced RF voltage, the J_x was reduced to about 1 (Δf_{RF} = + 7 Hz), in order to maximise the margin in RF voltage during the recovery from the trip. The RF trips are easily visible in Figure 8.

Figure 7: Display output (total RF voltage) of the computer program that automatically controlled J_x. The three cases correspond to 1 klystron off (upper left), recovering (upper right), and all normal (bottom).

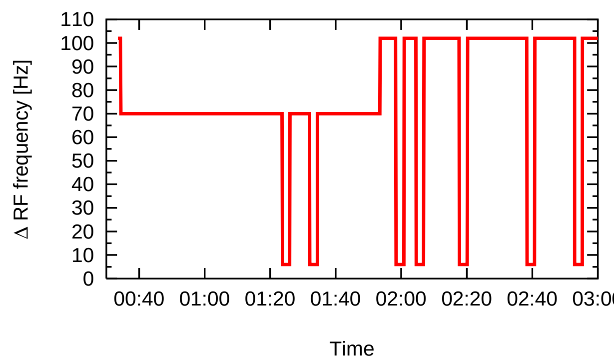

Figure 8: Shift of the RF frequency (with respect to the central frequency) versus time.

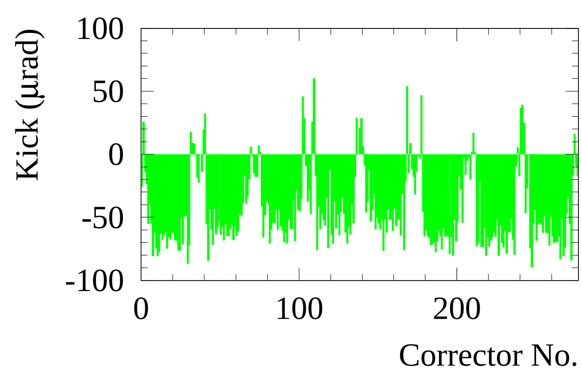

Figure 9: Corrector excitations around LEP during a typical high energy physics fill.*

* Figure provided by J. Wenninger.

2.4 *Average bending radius*

The energy loss per turn is a function of beam energy E and average bending radius ρ (compare Equation 1). The higher the average bending radius, the higher the beam energy that gives the same energy loss per turn. The average bending radius can be increased operationally by using additional bending contributions from quadrupoles and horizontal dipole correctors [5]. The principle is easily understood. Imagine, the LEP bending magnets provide 2π bending for a given beam energy. If additional bending is installed, the beam energy will adjust itself such that the total bending will again be 2π (with higher beam energy). The dipole magnets contribute now less than 2π to the total bending and the average bending radius (dominated from the dipole magnets) is increased. As a result higher beam energy can be achieved with the same accelerating RF voltage.

The dipole correctors of the horizontal orbit and the quadrupoles were used in LEP as additional bends. Figure 9 shows the excitations of dipole correctors in LEP during a typical high energy physics fill. The average bending radius of LEP was thus increased by 0.7 %, corresponding to an increase of maximum beam energy by about 0.2 GeV. 0.4 % of the total bending was then generated in the dipole correctors (two thirds) and the quadrupoles (one third).

2.5 *Highest beam energies with reduced margin in RF voltage*

The average length of physics fills depended on the available RF margin (the actual beam energy and the maximal available RF voltage) and the rate of RF trips. Its average value was given in Table 4 for different running scenarios. At maximum beam energy (without any margin) the average physics coast would only last 14 minutes, which is much less than its set-up time of about 60 minutes. Operation would be quite inefficient and the rate of luminosity production would be severely reduced. However, the Higgs discovery reach favours high energy against higher luminosity.

In order to combine high effective energy and acceptable luminosity production, a special ramping strategy was implemented ("mini-ramps"). A physics fill was started at a lower energy (2 klystrons margin), then ramped in collision to a medium energy (1 klystron margin) and ended with maximum energy (no margin). Due to the rapid transverse damping at the highest beam energies (60 turns at 104 GeV) it was possible to ramp the beams in collision, while the experiments continued data taking. The target energies were adjusted on a case-by-case basis, taking into account the available RF voltage and the klystron trip rate.

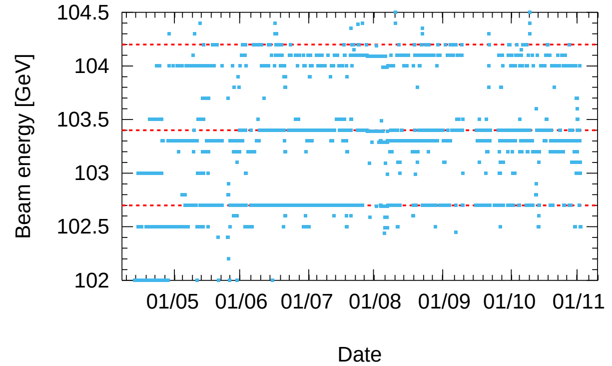

Figure 10: Beam energies with luminosity production versus time (LEP 2000 run). The red dotted curve indicates the three typical beam energies during a run (from bottom to top: 2, 1, and 0 klystron margin).

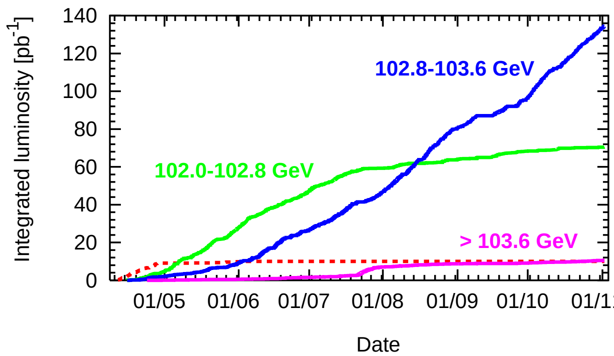

Figure 11: Luminosity production in 2000. The different curves represent different ranges of beam energy (2, 1, and 0 klystrons overhead). The dashed line indicates luminosity production below 102 GeV.

As a result many different beam energies were used during luminosity production in 2000. Figure 10 shows all beam energies with luminosity production versus time. The three typical beam energies (2, 1, 0 klystrons margin) are well visible and are indicated by red dotted lines. Three bands of high energy running can be distinguished:

1. 102.0-102.8 GeV: Lowest energy for luminosity production with a margin large enough to accommodate two klystrons off.
2. 102.8-103.6 GeV: Medium energy for luminosity production with a margin large enough to accommodate one klystron off.
3. 103.6-104.45 GeV: Highest beam energy for luminosity production. Any trip of a klystron caused an immediate beam loss.

The luminosity production in those three bands of energy is summarised in Figure 11. It is seen that most luminosity was initially produced in the band of 102.0-102.8 GeV, with a lesser but still very significant production at the higher beam energies. From middle of July onwards, most luminosity was produced between

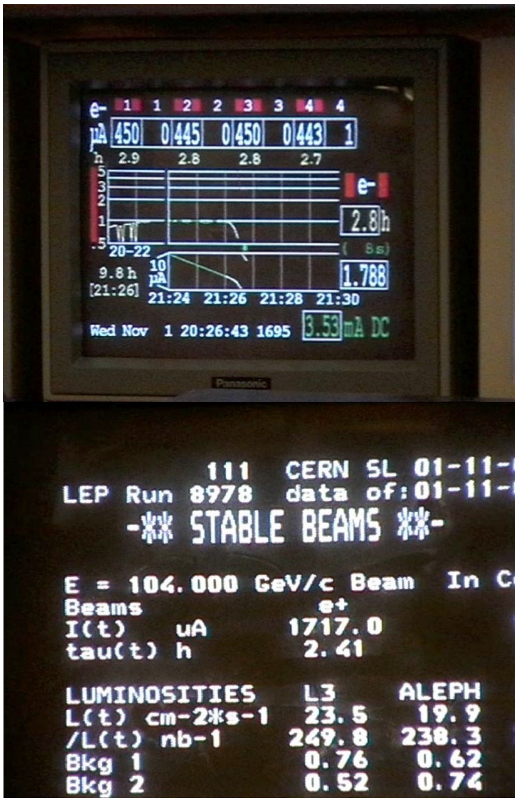

Figure 12: Beam lifetime and "page 1" for one of the last LEP runs at 104 GeV.

102.8 GeV and 103.6 GeV, with an increased production at the maximum beam energy around 104 GeV. The best sustained production rate at 102.8-103.6 GeV was 1.3 pb^{-1} per day. At 103.6-104.5 GeV the best sustained production rate was 0.55 pb^{-1} per day, with almost zero production at lower beam energies. The balance between effective energy and luminosity production rate was quantified and was constantly optimised for a maximum Higgs discovery reach.

The maximum beam energy was reached after ramping close to the quantum lifetime limit. At high energy the LEP current lifetime was limited from the beam-beam collisions. Depending on the achieved luminosity the lifetime typically varied between 5 and 9 hours [6,7]. However, as the energy was pushed close to the maximum beam energy, the lifetime became limited by the quantum lifetime. Figure 12 shows the current lifetime and the LEP "page 1" for one of the last LEP runs. The energy had been ramped to 104.0 GeV. At this energy the beam lifetime was about 2.5 hours (quantum lifetime), just long enough to avoid a too strong current decay during the expected length of luminosity production at this energy (14 minutes). Record beam energy of 104.45 GeV was reached with current lifetimes as low as 0.2-0.5 hours.

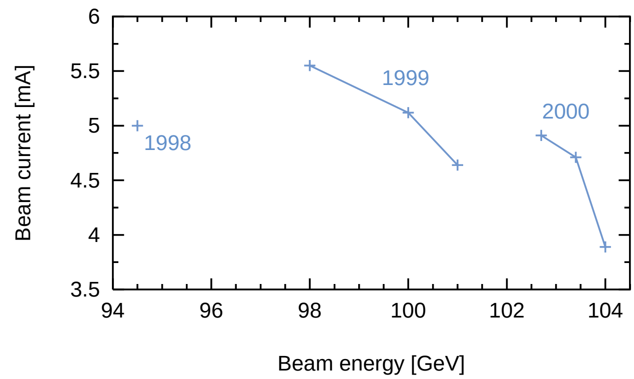

Figure 13: Average total beam current (in two times 4 bunches) for different beam energies from 1998 to 2000.

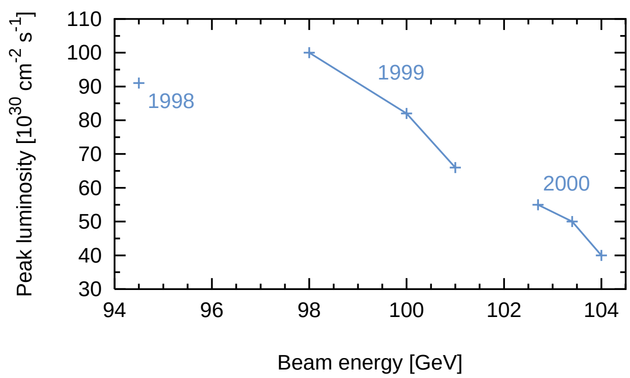

Figure 14: Peak luminosities for different beam energies from 1998 to 2000.

3 LUMINOSITY PERFORMANCE

The trade-off between beam energy and luminosity for LEP in 2000 favoured energy increases on cost of luminosity production. In addition to the "natural decrease" of luminosity with beam energy (higher energy spread with constant rms dispersion) the following factors caused a reduction in instantaneous luminosity:

1. The beam currents were limited at higher beam energies in order to increase RF stability and avoid excessive damage in the RF system. Figure 13 shows the average total current in both beams for beam energies used from 1998 to 2000. A substantial decrease below the highest value at 98 GeV is observed for the year 2000.
2. The J_x was set close to 1 for maximum energy reach in 2000, resulting in substantially larger horizontal IP spot sizes. For comparison, J_x was typically set to 1.6 in 1999.
3. The frequent energy ramping during a physics fill reduced the available time for luminosity optimisation at a given beam energy.

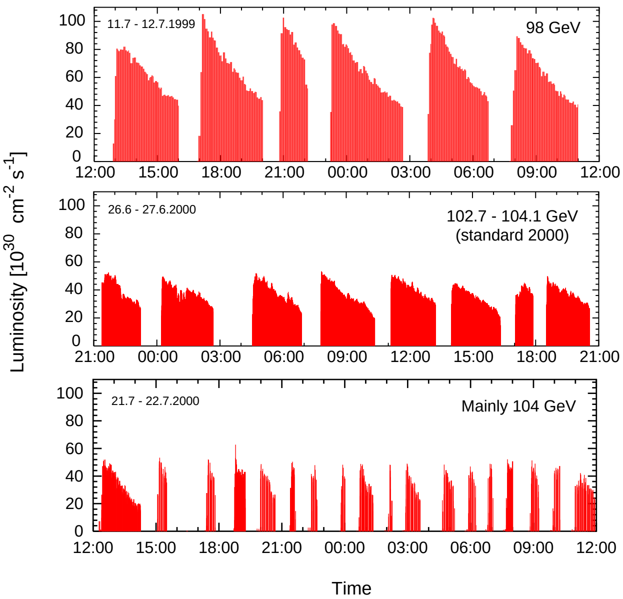

Figure 15: Instantaneous luminosity in LEP for three different days in 1999 and 2000. The selected days illustrate the different modes of operation for 98 GeV, 102.7-104.1 GeV (standard running 2000) and mainly 104 GeV.

Table 5: Average overhead time per physics fill (time from the end to the start of luminosity production).

Year	Overhead per fill
1998	110 min
1999	93 min
2000	65 min

The peak luminosity for the last three years of LEP operation is shown in Figure 14. Highest peak luminosity was reached for 98 GeV. The contributions to the excellent performance at 98 GeV are described in detail in [8,9]. Due to the trade-off between energy and luminosity, peak luminosities in the year 2000 were significantly below their highest values at 98 GeV. Nevertheless, operation still profited from the improvements in dispersion optimisation and tuning that were implemented during 1998 and 1999.

Figure 15 illustrates the different modes of running at 98 GeV (constant energy), at 102.7-104.1 GeV (a few mini-ramps), and mainly 104.1 GeV (early mini-ramp to highest energy) during three different days in 1999 and 2000. It is seen that the instantaneous luminosity and the length of physics fills were significantly reduced the higher the effective beam energy was pushed. As a consequence the number of physics fills increased dramatically over the last three years of LEP operation (from 436 fills with luminosity production in 1998 to 1356 fills in the year 2000). The increase is summarised in Figure 16.

The sharp increase in the number of physics fills did not only increase the workload for the operation crew but also reduced the efficiency of LEP. Each physics fill in

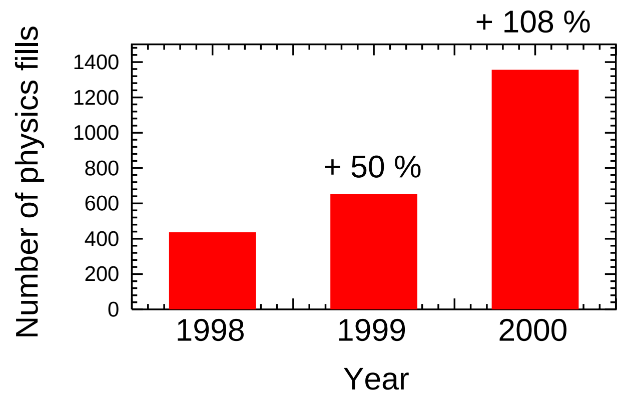

Figure 16: Number of physics fills with luminosity production in the last three years of LEP operation. The relative increase with respect to the previous year is indicated.

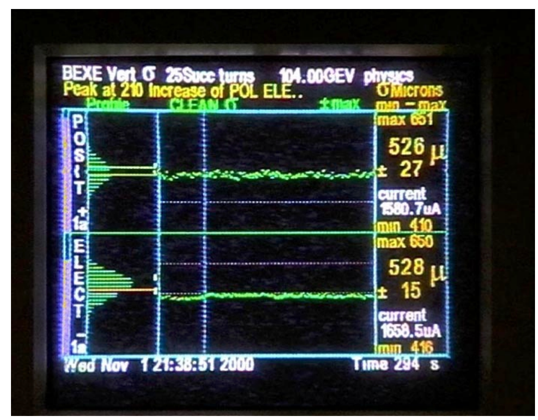

Figure 17: Vertical beam distributions and time histories of vertical beam size for positrons (top) and electrons (bottom) as measured in LEP at 104 GeV. The measurement was performed with the BEXE device [10].

LEP required an unavoidable turn-around for initialising the machine (degauss, collimators, tune settings, …), filling the required intensities at 22 GeV, ramping to the physics energy, and setting-up for luminosity production (collimators, golden orbits, tune adjustments, …). The turn-around was continually improved down to an average time of 65 minutes per physics fill in 2000 (with a typical fast turn-around of 45 minutes). Table 5 summarises the average turn-around time. It was reduced by 45 minutes from 1998 to 2000. This reduction was an important contribution to the excellent average rate of luminosity production in 2000.

Collider performances are often characterised using the vertical beam-beam parameter ξ_y. It is calculated from the measured luminosity L, the design vertical beta function β_y^* at the IP, the beam energy E, and the bunch current i_b:

$$\xi_y = \frac{2 r_e e m_e c^2 \cdot \beta_y^*}{n_b \cdot i_b \cdot E} \cdot L \qquad (3)$$

The term n_b denotes the number of bunches, r_e, e and m_e are the classical radius, charge and mass of the electron, and c is the light velocity. Re-expressing it in terms of the IP spot sizes σ_x^* and σ_y^*, it is seen that ξ_y is essentially a measure of the achieved beam cross-section at the IP:

$$\xi_y = \frac{r_e m_e \cdot \beta_y^* \cdot i_b}{2\pi\, e \cdot f_{rev} \cdot E \cdot \sigma_x^* \cdot \sigma_y^*} \qquad (4)$$

The measured vertical beam distributions and the time histories of the vertical beam size at 104 GeV are shown in Figure 17. Those local measurements (away from the IP) were routinely used for luminosity optimisation, together with other observables [7].

The ξ_y is closely related to the beam-beam tune shift per IP [11]. Naively we can assume $\sigma_x^* \propto E$ and $\sigma_y^* \propto E$ and we see that ξ_y would decrease with the third power of energy with the same machine imperfections. Numerous improvements in the performance of LEP counteracted and overcame this steep decrease.

The achieved values for ξ_y in LEP are summarised in Table 5 for different beam energies. Several other important machine parameters are listed as well. It is seen that the beam-beam parameter reached significantly higher values as the beam energy was increased. Above 65 GeV LEP did not reach the beam-beam limit. The increase of the beam-beam limit with beam energy is due to the rapid transverse damping for the highest LEP energies. Implementing many improvements and raising the beam current, a maximum vertical beam-beam parameter per IP of 0.083 was achieved in LEP.

The measured dependence of the beam-beam parameter on the bunch current is shown in Figure 18 for best performance. Though the beam-beam limit was not reached, some beam-beam related blow-up was observed. A beam-beam limit of ξ_y = 0.115 and an unperturbed vertical emittance of 0.1 nm was inferred from a fit [12]. The fitted curve was used for predictions of luminosity performance in LEP for different running scenarios.

An example for using the fitted dependence of luminosity on bunch current is shown in Figure 19. The calculated luminosity is shown versus the total current in the two beams both for 8 bunches (standard 4 on 4 running) and 4 bunches (2 on 2 bunches). The total beam current was limited to about 5 mA for 8 bunches (imposed from the RF system) and 3.6 mA for 4 bunches (single bunch limit due to transverse mode coupling instability at injection). It is seen that the achievable instantaneous luminosity for 2 on 2 bunches is only slightly below the luminosity that was routinely achieved for 4 on 4 bunches ($55 \cdot 10^{30}$ cm^{-2} s^{-1}), however, with a reduced luminosity lifetime.

Table 6: 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 τ_{transv} (in number of turns) for different beam energies in LEP. The collider was operating in beam-beam limited mode for 45.6 GeV and 65 GeV. The beam-beam limit was not reached for the higher beam energies. Up to 91.5 GeV a 90/60 optics, above 91.5 GeV a 102/90 optics were used.

Beam energy [GeV]	**ξ_y (max) per IP**	**β_x^*/β_y^* [m]**	**i_b [μA]**	**J_x**	**τ_{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

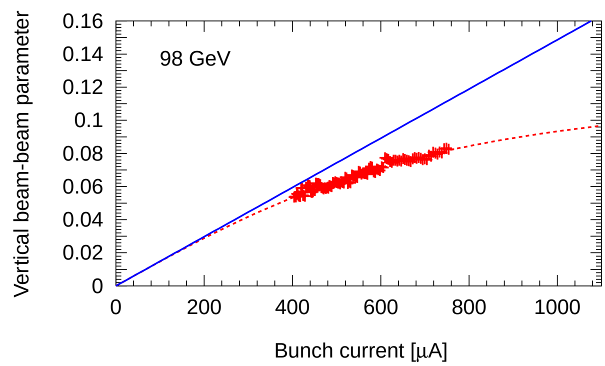

Figure 18: Vertical beam-beam parameter versus bunch current. The data is compared to the not beam-beam limited case (solid line) and a beam-beam fit (dashed line) [12].

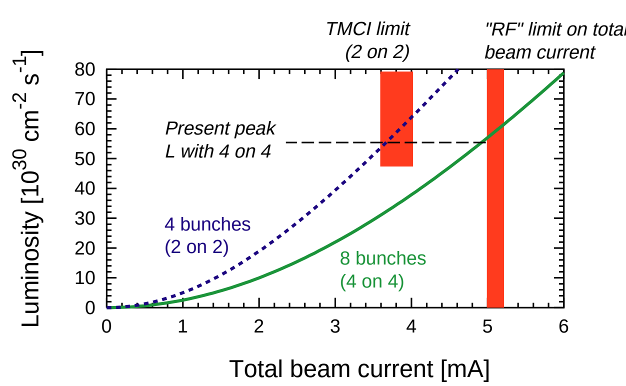

Figure 19: Calculated luminosity versus beam current for 2-on-2 and 4-on-4 bunches, based on a fitted beam-beam limit of 0.115 per IP. The limits for the single bunch current (TMCI) and total current are indicated.

Figure 20: Instantaneous luminosity, total beam current, and beam energy during 4 on 4 bunch (start and end) and 2 on 2 bunch (16:00 – 7:00) operation.*

It was hoped that the lower total current for 2 on 2 bunches would result in a better RF stability with a subsequent increase of the effective energy for luminosity production. The option to run with 2 on 2 bunches was tried for a short period of time (see Figure 20). With 40% less total current, the luminosity was reduced by about 30% (due to the limited time for orbit optimisation). However, no significant improvement in RF stability was observed and this way of running was abandoned.

5 CONCLUSIONS

The Large Electron-Positron Collider (LEP) at CERN completed its operation in 2000. Electron-positron collisions were established at centre-of-mass energies of up to 209 GeV. The maximum energy reach of LEP collisions was thus extended by another 7 GeV, compared to the year 1999. The luminosity rate was kept high, yielding a total delivered luminosity of 233 pb^{-1} in 2000. High beam energy and high luminosity allowed for an extended discovery reach of LEP. The LEP experiments ALEPH and L3 reported on several candidate events for the Higgs boson [13,14].

The successful energy increase of LEP was analysed in detail and the performance in the regime of ultra-strong damping was described. A maximum beam-beam parameter of 0.083 per interaction point was achieved in LEP during 1999. The beam-beam limit was not reached for operation with beam energies above 65 GeV. Using fits of the beam-beam data, the beam-beam limit was inferred to be about 0.115 per interaction point (above 98 GeV).

The operational overhead per physics fill was reduced from 110 min in 1998 to 65 min in 2000, maximising the time available for physics. At the same time the number of physics fills increased from 436 to 1356 per year.

On November 2nd, 2000 the LEP beams were permanently shut down (compare Figures 21 and 22) and dismantling of the accelerator started. This ended the "life" of the highest energy electron-positron collider to date and one of the largest machines that mankind has built.

6 ACKNOWLEDGEMENTS

This is the last of 554 contributions on LEP to the Chamonix workshop, authored by 118 different scientists. The results presented here were made possible only because of this impressive foundation. Everything is based on the huge amount of scientific and technical work undertaken at CERN by many, many people over the last 23 years. O. Brunner, A. Butterworth, P. Janot, M. Lamont, and J. Wenninger provided data or a figure for this report.

* Figure provided by M. Lamont.

Figure 21: Ceremonial dump of the last physics fill in LEP on November 2nd, 2000.

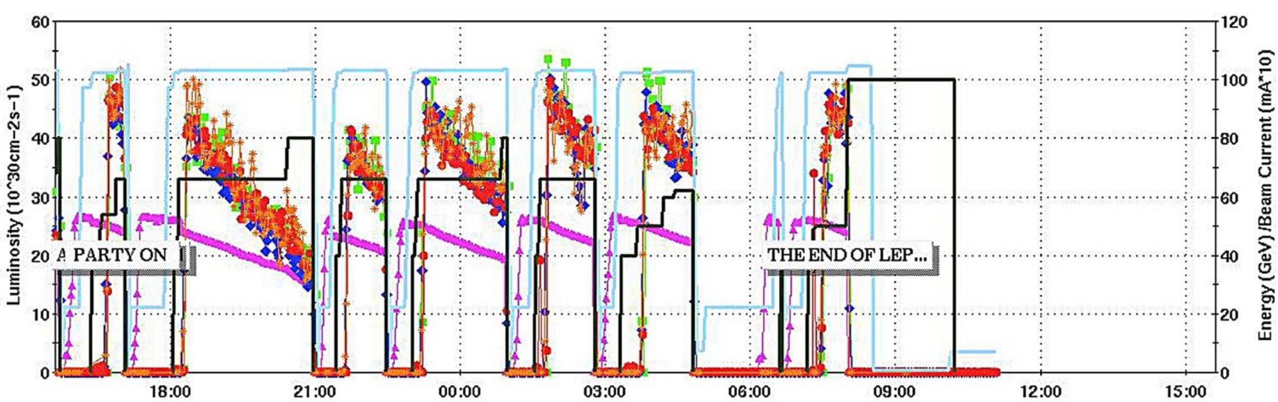

Figure 22: The end of LEP.

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