LEP LUMINOSITY REVISITED: DESIGN AND REALITY

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Abstract

The Large Electron-Positron collider (LEP) operated in the years 1989 to 2000 at CERN, many years well above design parameters. LEP was the largest particle accelerator to date, supporting the exploration of the Particle Physics Standard Model with hitherto not achievable precision. The LEP luminosity performance is revisited in this paper. Some major ingredients to luminosity are analysed and compared to the original design. We include practical considerations, like the time required to achieve and surpass design parameters. More fundamental accelerator physics observations concern the behaviour of the beam-beam limit in the regime of ultra-strong radiation damping.

1 INTRODUCTION

A first LEP study group was formed at CERN in 1976. CERN's Council approved the LEP project at the end of 1981 with a detailed "LEP Design Report" published in 1984 [1]. The LEP collider was subsequently constructed and started its operation in 1989, thirteen years after the initial design studies. It operated for eleven years until the end of the year 2000, pushing particle and accelerator physics into regimes of hitherto unknown precision and performance. In terms of particle physics reach, the judgment of the LEP performance is based on:

1. The **delivered luminosities**.
2. The range in **beam energy**.
3. The accuracy in beam **energy calibration**.

This paper revisits the luminosity performance of LEP and describes some of the ingredients to the success of LEP. Wherever possible, the achieved performances are put into perspective by comparison with the original design parameters. Clearly, this cannot be a full and fair review of all the LEP achievements. Additional results and details can be found in [2-4]. In particular the achievement of high energy is not discussed in this paper, but can be studied in [5-7]. Also, the work on polarized beams [8] and precise energy calibration [9,10] is not discussed.

2 DESIGN OVERVIEW

Looking back at LEP it is interesting to compare the LEP design parameters [1,11] and the actually achieved performances. 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 [1] and [11] and were not adjusted for this discrepancy, as the changes would be small. This was shown in [12] where the LEP design parameters were explored as a function of beam energy. Alternative working points, as described e.g. in [13], are also ignored.

The design and achieved values for a number of crucial LEP performance parameters are summarized in Table 1. 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.

Table 1: Comparison of design and achieved values for a few important LEP performance parameters.

Parameter	**Design** LEP1 / LEP2	**Achieved** LEP1 / LEP2
Bunch current	0.75 mA	1.00 mA
Total beam current	6.0 mA	8.4 / 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}
IP beta function β_x	1.75 m	1.25 m
IP beta function β_y	7.0 cm	4.0 cm
Max. beam energy	95 GeV	104.5 GeV
Av. RF gradient	6.0 MV/m	7.2 MV/m

3 PEAK LUMINOSITY

The peak luminosity is shown in Figure 1 for each year of LEP operation. The design luminosities are indicated for both LEP1 and LEP2.

3.1 Peak Luminosity at LEP1

Already in the commissioning year 1989 it was possible to achieve 25% of design peak luminosity with an improvement to 70% in the first full year of LEP running. The LEP1 performance was generally limited due to the beam-beam effect. Operating at the beam-beam limit, the bunch currents were limited to about 0.32 mA from unstable beam-beam modes, beam-beam tails and particle background in the experiments. The beam-beam effects were alleviated by blowing-up the spot sizes with wigglers, limited however from the available machine aperture and background problems. In order to improve the luminosity for a given bunch current, it was tried to maximize the number of bunches in the machine. Luminosity should ideally increase linearly with the number of bunches, if the same bunch current is used. Several bunch schemes were used in LEP:

1. Nominal 4 on 4 bunches (1989-1992, 1996-2000).
2. 8 on 8 bunches with Pretzel orbits (1992-1994).
3. Bunch trains with a crossing-angle (1995).

The use of pretzel orbits (horizontal separation orbits) proved very successful and allowed reaching and surpassing the LEP1 design luminosity in the fifth year at 45.6 GeV. Highest luminosity at 45.6 GeV was reached with bunch train operation in the seventh year. In summary, the LEP1 peak luminosity reached about 210% of its design value.

3.2 Peak Luminosity at LEP2

The situation was qualitatively different for LEP2 beam energies, where the beam-beam limit was not reached and much higher bunch currents (up to ~ 0.8 mA) could be collided (see Section 5). As soon as the beam energy was raised above 50 GeV the LEP2 design luminosity was surpassed. The increase of the horizontal beam size with beam energy was partly compensated with a stronger focusing optics [14] and changes in the damping partition numbers [15]. The highest LEP2 luminosities reached about 400% of the LEP2 design value. In 2000 the peak luminosity was voluntarily reduced in order to maximize the beam energy [7,15].

4 INTEGRATED LUMINOSITY

The integrated luminosity that is delivered to the experiments is a function of the instantaneous (peak) luminosity and the accelerator efficiency. The accelerator efficiency 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 efficiency was constantly improved over the years:

1. A thorough cold-checkout minimized the number of problems to be fixed with beam.
2. A vertical realignment of all quadrupoles ensured faster set-up of nominal luminosity conditions.
3. The operational procedures were constantly improved for a faster set-up of luminosity runs.

The importance of those 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.

At the highest LEP2 energies the length of physics fills was only 1.5 hours, much shorter than the 12 h physics fills at the Z energy. An even better efficiency was crucial for a good LEP2 performance.

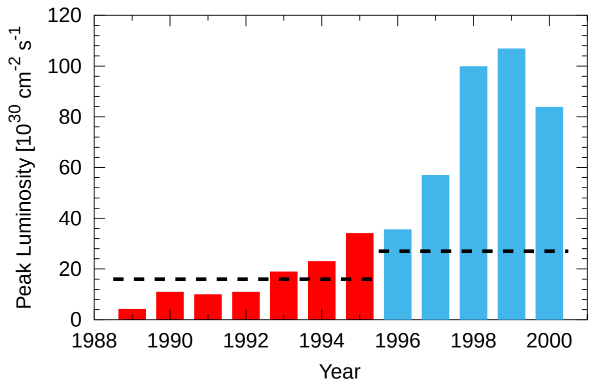

Figure 1: Peak luminosity for each year of LEP operation. The dashed lines indicate the design luminosities for LEP1 (red bars) and LEP2 (blue bars).

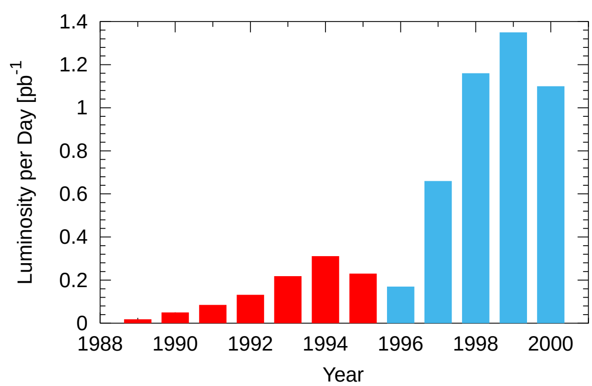

Figure 2: Average luminosity delivered per scheduled day of physics for each year of LEP operation. The red bars indicate LEP1 running, the blue bars LEP2 running.

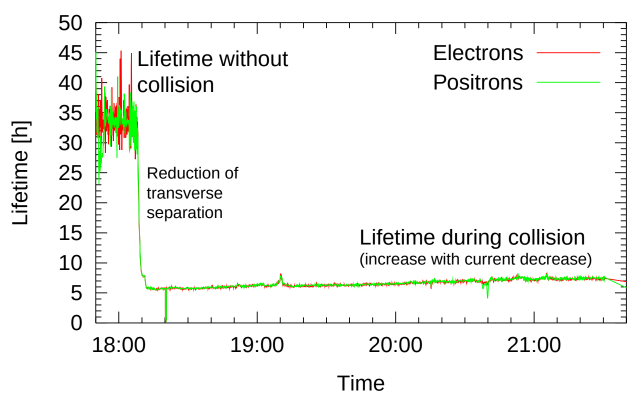

Figure 3: Evolution of beam lifetime in LEP.

Reliable luminosity production depends in addition on a well-behaved machine in terms of beam losses or beam lifetime. The beam lifetime during a high energy physics fill is shown in Figure 3. The regular behaviour of the beam lifetime is clearly visible. All contributions to the LEP beam lifetime have been analysed and are well understood [16].

Table 2: 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. The beam-beam limit was not reached for beam energies above 65 GeV. Mainly a 90/60 optics was used up to 91.5 GeV, a 102/90 optics was used above 91.5 GeV.

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

5 THE BEAM-BEAM LIMIT

The beam-beam effect in LEP has been discussed in numerous papers [17-21]. Collider performances are 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:

$$\xi_y = \frac{2\, r_e e\, m_e c^2 \cdot \beta_y^*}{n_b \cdot i_b \cdot E} \cdot L \qquad (1)$$

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. One can re-express ξ_y in terms of the IP spot sizes σ_x^* and σ_y^*:

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

The value of ξ_y is a measure of the achieved beam cross-section at the IP and is closely related to the beam-beam tune shift per IP [22,23]. For dispersion dominated spot size we have $\sigma_x^* \propto E$ and $\sigma_y^* \propto E$ and ξ_y would decrease with the third power of energy for the same dispersion. Improvements both in horizontal (optics) and vertical (orbit) dispersion prevented this steep decrease.

The achieved values for ξ_y in LEP are summarised in Table 2 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.

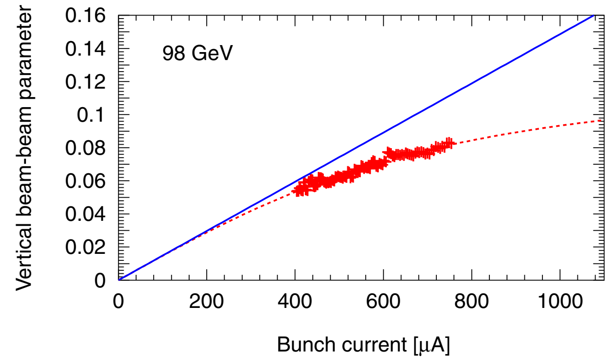

Figure 4: Vertical beam-beam parameter versus bunch current. The data is compared to the not beam-beam limited case (solid line) and a beam-beam fit (dashed line) [24].

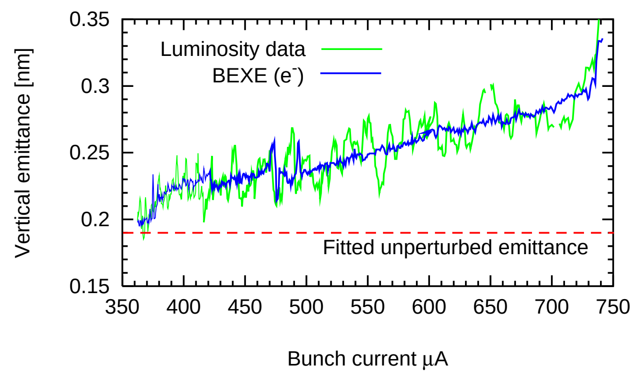

Figure 5: The vertical emittance as fitted and calculated from luminosity and synchrotron beam size measurements (BEXE) [24,25].

The measured dependence of the beam-beam parameter on the bunch current is shown in Figure 4 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 simple model [24]. In order to verify that the observed saturation in ξ_y is correctly attributed to the beam-beam effect, we consider the current dependent blow-up of the vertical emittance. The luminosity data allows calculating the vertical emittance, assuming that the optical functions are known and that the horizontal emittance has its design value. The luminosity data is compared with the measured vertical beam size in the BEXE instrumentation [25,26] in Figure 5. The vertical emittance blow-up calculated from the measured luminosity is consistent with the blow-up observed from the BEXE beam size. At lower bunch current the vertical emittance approaches its fitted unperturbed value.

It has been observed before that the beam-beam limit ξ_y^∞ is a function of the transverse damping time τ, the revolution frequency f_{rev} and the number n_{IP} of interaction points [27]:

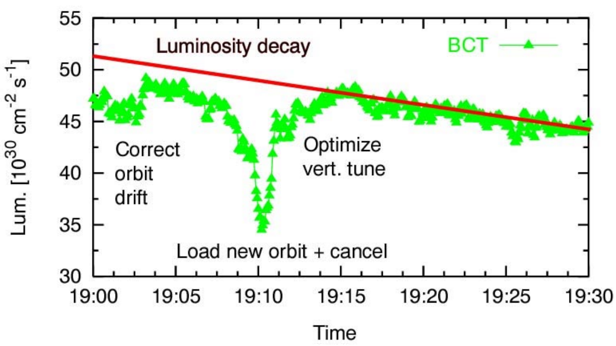

Figure 6: Example of empirical luminosity tuning as observed with the current lifetime (BCT).

$$\xi_y^{\infty} = \mathrm{f}\left[\lambda_d\right] = \mathrm{f}\left[\frac{1}{f_{rev}\cdot\tau\cdot n_{IP}}\right] \tag{3}$$

The damping decrement is denoted by λ_d. The functional dependence is unknown. Based on observations in different colliders a parameterisation $\xi_y^{\infty} \propto \lambda_d^{0.3}$ was suggested by Keil, Talman, and Peggs [27,28]. The LEP data for 94.5-101 GeV consistently suggest a beam-beam limit of around 0.115. Comparing this to the observed beam-beam limit of 0.045 at 45.6 GeV we find a scaling:

$$\xi_y^{\infty} \propto \lambda_d^{0.4} \tag{4}$$

This is more optimistic but reasonably close to the earlier result from Peggs [28].

6 ORBIT OPTIMISATION

The luminosity at LEP required constant tuning. It was optimised with a "golden orbit" strategy. Orbits were changed empirically, sometimes in combination with other parameters. If the luminosity increased the change was kept, otherwise it was reverted. Local measurements of beam size (away from the IP), beam-beam deflection scans etc were routinely used for luminosity optimisation [26,29-31]. The beam lifetime was used as the fastest luminosity measure. An example of empirical orbit and tune optimisation is shown in Figure 6.

A "dispersion-free steering" algorithm [32] was introduced during the last three years of LEP operation. This algorithm simultaneously minimizes the vertical orbit, vertical dispersion, and the corrector strengths. The performance of this fast and deterministic algorithm is illustrated in Figure 7. The vertical dispersion was reduced to values previously not achievable and the time required for empirical tuning was significantly reduced. As a result the vertical dispersion was reduced from ~3 cm to ~1.5 cm with a significant vertical emittance improvement expected from simulations (Figure 8). Indeed, the emittance ratio was improved from the 1.5% to the 0.4% level, as shown in Figure 9. This was 10 times smaller than estimated in the original design.

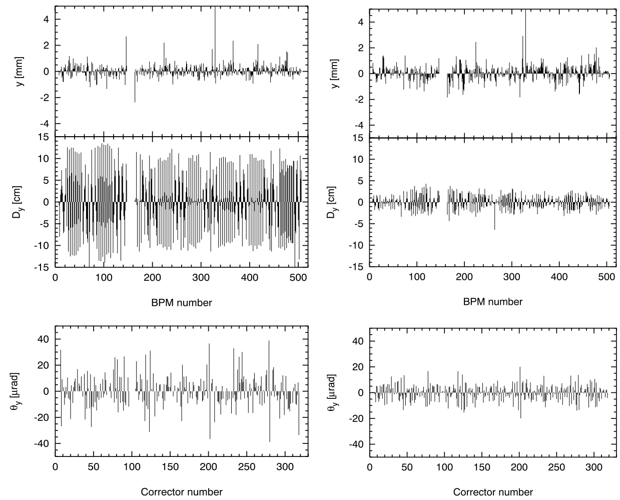

Figure 7: Measured vertical single beam orbit, dispersion, and corrector settings versus BPM number after standard MICADO steering (left) and after dispersion-free steering (right).

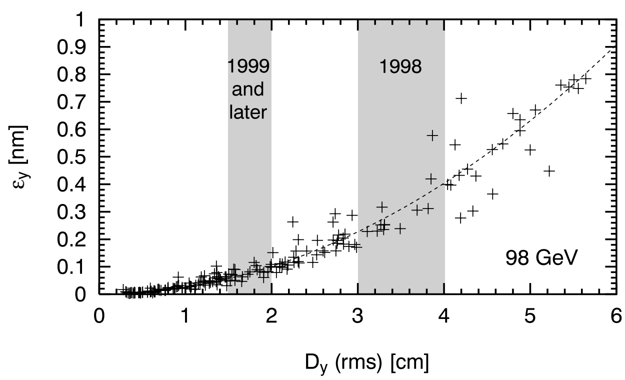

Figure 8: Simulated dependence of the vertical emittance on the RMS dispersion in LEP with bands of typically achieved dispersions during 1998 and 1999. Each point represents a specific case of imperfections.

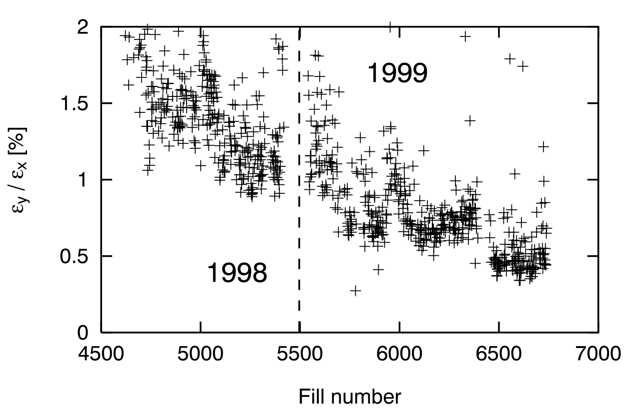

Figure 9: Average emittance ratio $\varepsilon_y/\varepsilon_x$ (in %) for bunch currents between 500 μA and 550 μA and all high energy physics fills in 1998 and 1999.

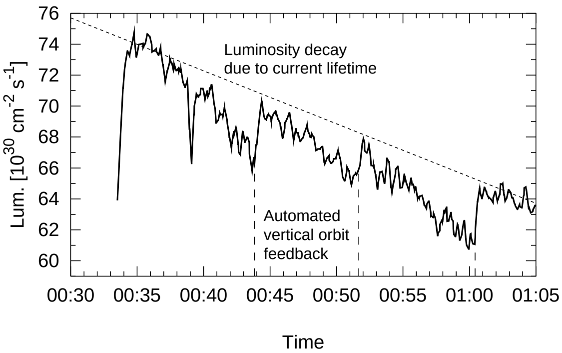

Figure 10: Measured luminosity versus time. The dashed lines indicate vertical orbit corrections from an automated orbit feedback.

Once optimised, the 27 km long LEP orbit had to be stabilized on the 0.01 mm level. An orbit "autopilot" was used for automatic correction of the vertical orbit about every 7 minutes. The luminosity loss due to orbit drifts and the restoring effect of an automatic orbit feedback are shown in Figure 10.

7 CONCLUSION

The LEP collider at CERN was commissioned in 1989 and operated until the end of the year 2000. It performed many years above design expectations. In particular it was possible to push the instantaneous luminosity a factor of 4 above its design value, at higher beam energies than foreseen in the design.

The instantaneous luminosity already reached 70% of its design value in the second year of LEP operation. This illustrates the sound design strategy for LEP1, the great care in the accelerator construction, and the good knowledge of the relevant accelerator physics for LEP1. To surpass the design luminosity at LEP1 required four years and an increased number of bunches, originally not foreseen in the design.

The accelerator physics in the LEP2 regime of ultra-strong radiation damping was not well known. As a result the design estimate of the luminosity turned out to be too pessimistic. Taking profit of a much higher beam-beam limit, strong focusing optics, and manipulations of the damping partition numbers the design luminosity was immediately surpassed.

As it is true for all colliders, the final luminosity performance was only possible due to many ideas and concepts that were not foreseen in the original design.

ACKNOWLEDGEMENTS

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