ELECTRON-POSITRON COLLISIONS AT 209 GEV IN LEP

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Abstract

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

1 INTRODUCTION

The LEP discovery reach for the Standard Model Higgs boson was pushed from 95 GeV/c^2 in 1998 to around 113 GeV/c^2 in 2000 [1]. This increase was the result both of the increase of beam energy and the higher than expected luminosity production at these higher beam energies. How this was achieved are analysed herein.

Table 1 summarises the maximum beam energies, integrated luminosities and the average rate of luminosity production for 1994 to 2000. The LEP performance was improved significantly over the years. From the total of 1000 pb^{-1} per experiment delivered between 1989 and 2000 almost 70 % were delivered in the last three years.

The Higgs discovery reach of LEP was maximised by a trade-off between luminosity and energy, some luminosity being sacrificed in the interest of production at the highest possible energies. This is discussed in detail in [1]. It is seen from Table 1 that the peak performance of 1999 was not reached during 2000. This reduction reflects the trade-off between maximising beam energy and integrated luminosity.

Year	Beam energy [GeV]	Total luminosity [pb^{-1}]	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

Table 1: Overview of LEP performance 1994-2000.

2 MAXIMUM BEAM ENERGY

The maximum operational energy of LEP depended on a number of different parameters [2,3]:

Available accelerating RF voltage Installation of LEP2 superconducting cavities ended in 1999. There was therefore very little additional RF hardware at the start of the 2000 run. The main gain came from raising the accelerating gradient of the super-conducting RF cavities well above the design value of 6 MV/m [4].

Rate of RF trips The RF system was protected with about 10,000 interlocks. Interlocks can trip one klystron (~ 100 MV), 2 klystrons, or dump the beam. Trips occurred on a statistical basis and were mainly produced by field emission, causing Helium level or pressure problems. Recovery was fast (~ 2 min). The trip rate determined the required operating RF voltage margin: by working at an energy lower than the maximum possible it was possible to have RF trips and keep the beam [4]. The RF stability was improved with fast GPS based diagnostics, active damping of field oscillations and various hardware improvements.

Maximum horizontal beam size 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:

$$\sigma_x \propto \sqrt{\beta_x / J_x} \cdot D_x^{rms} \cdot E$$

The increase of horizontal beam size with energy results in lower luminosity and larger background in the experiments. This compensated for by the use of a high Q_x optics [5] and an increase of J_x through an increase of the RF frequency. Up to 91.5 GeV a 90°/60° optics was used, above 91.5 GeV a 102°/90° optics took over. The tactic of increased J_x reduces both beam energy and increases the RF voltage required (larger energy spread). For maximum beam energy, however, one should run with the lowest J_x possible, and indeed, in 2000 increased horizontal beam size was accepted in the interests of increasing the beam energy.

Average bending radius The energy loss per turn is a function of beam energy E and average bending radius ρ. The average bending radius can be changed operationally by using the horizontal dipole correctors [6].

The LEP energy was maximised in 2000 by optimising all of the above contributions. Due to the cost in energy of the RF voltage margin (200 MV corresponded to ~1.6 GeV) a special ramping strategy was implemented. A physics fill was started at an energy equivalent to a 2 klystrons margin, after a while the beam was then

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ramped, under physics conditions, to an energy equivalent to a 1 klystron margin. Towards the end of a fill the beam energy was ramped to the maximum (no RF margin), the end of fill being given by the next RF trip. The contributions to the energy gain of 3.4 GeV in 2000 with respect to 1999 is shown in Table 2. Luminosity production throughout 2000 at different energies is illustrated in Figure 1.

Contribution	**Energy gain**
Additional RF cavities	0.14 GeV
Higher RF gradient	0.96 GeV
Less RF margin	1.60 GeV
Reduced RF frequency	0.70 GeV
Increased bending radius	0.17 GeV
Total	**3.53 GeV**

Table 2: Contributions to the energy increase in 2000.

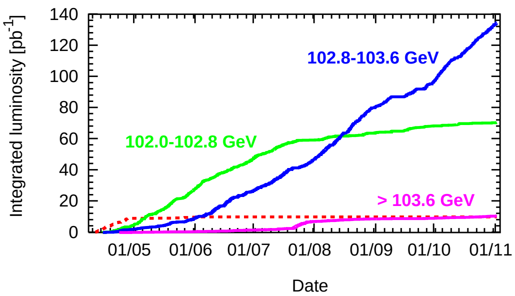

Figure 1: Luminosity production in 2000. The three ranges correspond to 2, 1 and 0 klystrons margin (right hand numbers, from top to bottom).

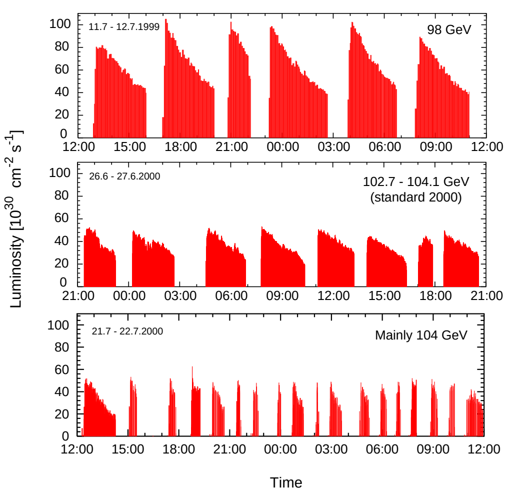

Figure 3: Instantaneous luminosity in LEP for three different days in 1999 and 2000. The different modes of operation for 98 GeV, 102.7 to104.1 GeV (standard running in 2000) and mainly 104 GeV are clearly visible.

3 LUMINOSITY PERFORMANCE

Luminosity production was highest in 1999, as can be seen from Table 1. Figure 2 shows the peak luminosity versus energy for the physics fills in 1998, 1999, and 2000. The beam-beam limit was not reached for beam energies above 70 GeV. The peak luminosities came down when the beam energy was raised to 100 GeV and 101 GeV. The decrease of luminosity continued with the higher beam energies in 2000. The reduction is mainly due to lower beam currents, shorter fills and larger horizontal beam sizes (see discussion above). Three different modes of LEP running are illustrated in Figure 4: 98 GeV with a large RF voltage overhead (horizontal beam size reduced aggressively with J_x=1.7), mini-ramp strategy in 2000, and dedicated running at 104 GeV without any overhead.

Energy [GeV]	**ξ_y 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

Table 3: 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.

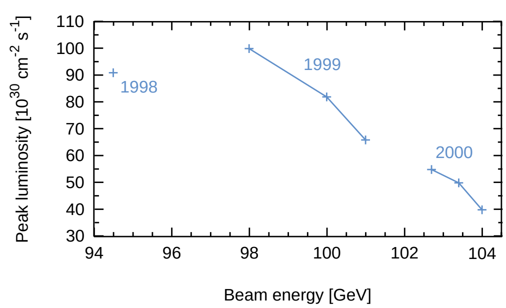

Figure 2: Peak luminosity in all physics fills between 1998 and 2000.

Peak luminosities reached 10^{32} cm^{-2} s^{-1} and the vertical beam-beam parameter 0.083 per IP at 98 GeV. A higher beam-beam limit at high energy is the result of the strong transverse damping (60 turns at 104.4 GeV compared to 721 turns at 45.6 GeV - see Table 3). Figure 4 shows the vertical beam-beam parameter for a 98 GeV fill versus bunch current. The data is compared to the expected behaviour without beam-beam blow-up and a fit [10]. From the fit a beam-beam limit can be inferred at ξ_y=0.115 and an unperturbed vertical emittance of 0.1 nm. Though there was an emittance blow-up of up to ~70%, LEP did not reach the beam-beam limit at high energies.

The strong transverse damping allowed a jump of the third integer resonance for a high Q_x working point of 0.36 with both better luminosity and backgrounds.

The release from the beam-beam limit allowed thorough optimisation of the vertical beam size and considerable reduction was achieved by targeting coupling and residual vertical dispersion.

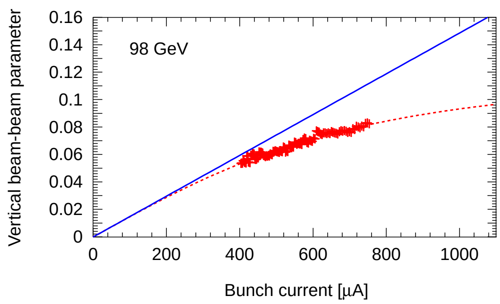

Figure 4: Vertical beam-beam parameter versus bunch current. The data is compared to the not beam-beam limited case and a fit [10].

The integrated luminosity was optimised by both maximising the instantaneous luminosity and the time available for physics. As shown in Table 4, the overhead due to the magnet cycling, injection at 22 GeV, ramping to high energy and setting up for physics was reduced from 110 min in 1998 to 65 min in 2000. Higher beam intensities from the injector chain, increased injection efficiency, and double ramp speed contributed to this important improvement. In addition, an automated control of the horizontal damping partition number J_x (as a function of the available RF voltage) was implemented.

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

Table 4: Average overhead per physics fill.

4 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 was thus extended by another 7 GeV with respect to 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. In particular, the LEP experiments reported candidate events for the Higgs boson [11,12].

Performance highlights in the regime of ultra-strong damping included a maximum beam-beam parameter of 0.083 per interaction point, achieved 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 was shut down for good (see Figure 5) 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.

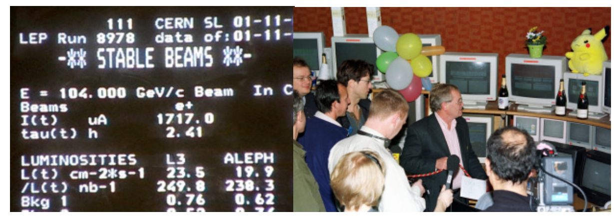

Figure 5: The public LEP page for one of the last physics fills at 104 GeV (left) and the ceremonial dump of the last physics fill in LEP on November 2nd, 2000 (right).

5 ACKNOWLEDGEMENTS

The results presented are based on the scientific and technical work from many hundred people at CERN over the last 23 years. We gratefully acknowledge their work.

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