EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN — SL DIVISION

CERN - SL-2000 - 045 OP

LEP OPERATION AND PERFORMANCE WITH 100 GEV COLLIDING BEAMS

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Paper presented at EPAC 2000
26 - 30 June 2000, Vienna, Autria

Geneva, Switzerland
June 2000

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Abstract

Luminosity production in LEP was extended to 101 GeV beam energy in 1999 and 104.4 GeV in 2000. The performance was continually optimised, resulting in 1999 peak and integrated luminosities higher than in any previous year of LEP operation. In particular, the beam-beam tune shift reached 0.083 per interaction point. This was achieved with the help of a faster luminosity monitoring, a new tune working point, a reduced design vertical dispersion and new dispersion and coupling optimisation tools. A higher beam rate from the injectors, a better injection efficiency, a faster ramp and a newly automated control of the horizontal damping partition number J_x maximised the time available for physics and thus contributed to the higher integrated luminosity.

1 INTRODUCTION

The main objective of high-energy operation of LEP is the data production for precision studies of the W boson and for the search of new particles. Table 1 summarises the maximum beam energies, maximum beam-beam parameters ξ_y (per interaction point), integrated luminosities and the average rate of luminosity production for 1994 to 2000. The LEP performance was improved significantly over the years. As a consequence, the statistical error on the W-mass in 1999 was close to its systematic error [1]. In this situation it has become more important to produce luminosity at the highest possible energies, even if the integrated luminosity is reduced. The discovery reach of LEP, for example for the Higgs boson, is thus maximised. This is discussed in detail in [1]. It is seen from Table 1 that the peak performance from 1999 is not being reached during 2000. This reduction reflects the trade-off between maximising beam energy and integrated luminosity.

2 MAXIMUM BEAM ENERGY

The maximum operational energy depends on a number of different parameters:

Available accelerating RF voltage. Its evolution is shown in Figure 1. It was increased by installing additional RF cavities and raising the accelerating gradient of the super-conducting RF cavities from 6 MV/m (design) to 7.4 MV/m.

Rate of RF trips. The RF system is protected with about 10000 interlocks. Interlocks can disrupt one klystron (~ 100 MV), 2 klystrons or the beam. Trips occur on a statistical basis and are mainly produced by field emission, causing Helium level or pressure problems. The recovery is fast (~ min). The trip rate determines the required overhead in RF voltage. As it depends on beam current [3], the intensity at highest energies is operationally limited, also minimising transient voltage reductions during trips. The RF stability was improved with fast GPS based diagnostics, active damping of field oscillations and various hardware improvements.

Table 1: Overview of LEP performance 1994-2000

Year	Beam energy [GeV]	Maximum ξ_y	Total luminosity [pb^{-1}]	Average luminosity rate [pb^{-1}/day]
1994	45.6	0.045	64	0.31
1995	45.6 – 70.0	0.050	47	0.23
1996	80.5 – 86.0	0.040	25	0.17
1997	91.0 – 92.0	0.055	75	0.66
1998	94.5	0.075	200	1.16
1999	96.0 – 101.0	0.083	254	1.35
2000*	100.0 – 104.3	0.055	71	0.96

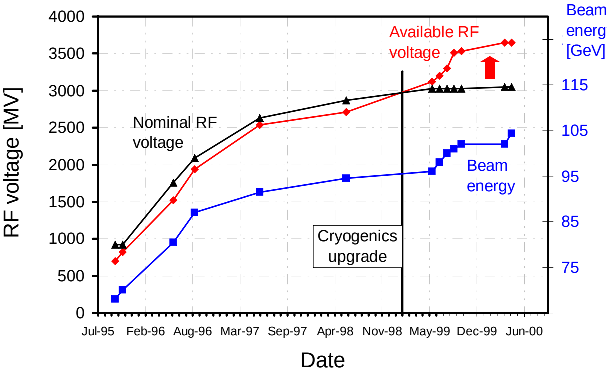

Figure 1: Evolution of beam energy, nominal RF voltage (design gradient) and available RF voltage [2].

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 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). For maximum beam energy it is desirable to run with the largest σ_x (lowest J_x) possible.

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 opera-

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[*] Status 15.6.2000.

tionally by using additional bending contributions from quadrupoles and horizontal dipole correctors [4].

Table 2: Contributions to the energy increase in 2000.

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**

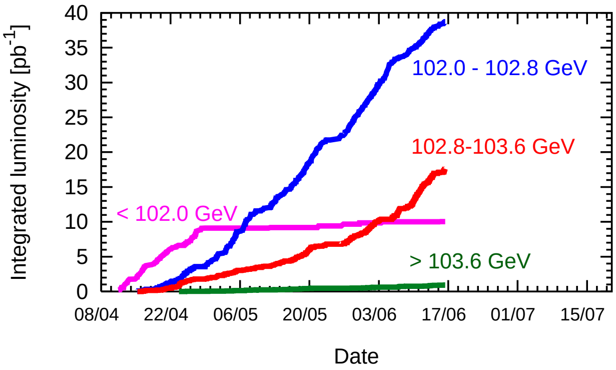

Figure 2: Luminosity production in 2000. The three ranges correspond to 2, 1 and 0 klystrons overhead (right hand numbers, from top to bottom).

The LEP energy has been maximised in 2000 by optimising all of the above contributions. Due to the large cost of the RF voltage overhead (200 MV correspond to ~1.6 GeV) a special ramping strategy was implemented. A physics fill is 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). The energy gain from 1999 (101 GeV) to 2000 (104.4 GeV) is analysed in Table 2. Luminosity production is illustrated in Figure 2.

3 LUMINOSITY PERFORMANCE

Luminosity production was best in 1999, as can be seen from Table 1. Figure 3 shows the peak luminosity for physics fills in 1998 and 1999. Best performance was achieved at 98 GeV. The peak luminosities were reduced 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 of beam energy).

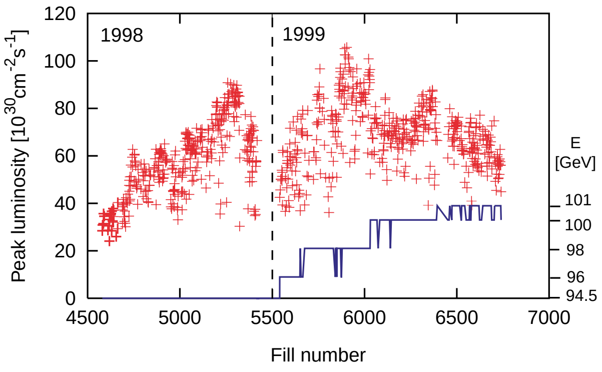

Figure 3: Peak luminosity in all physics fills in 1998 and 1999. The line indicates the beam energy.

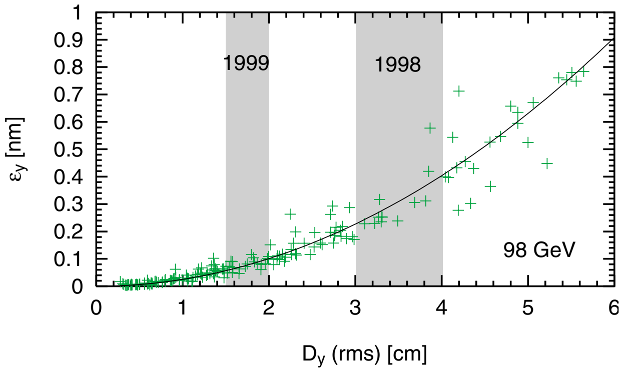

Figure 4: Simulated relationship between vertical rms dispersion and vertical emittance. The grey bands indicate 1998 and 1999 values of measured dispersion.

3.1 Peak performance

Best performances were obtained at 98 GeV with peak luminosities of 10^{32} cm^{-2} s^{-1} and a vertical beam-beam parameter of 0.083 per interaction point. We discuss the contributions:

A large overhead in RF voltage made it possible to push the beam currents to the maximum (6.4 mA), to reduce the horizontal beam size aggressively (J_x=1.7), and to keep the fill length optimal.

A deterministic orbit and dispersion correction was implemented for LEP (Dispersion-free Steering DFS). The method is described in [5]. In combination with an optics improvement for the vertical separation bumps, it allowed the fast and deterministic reduction of the vertical rms. dispersion D_y^{rms}. At high energy the vertical emittance is mainly produced by D_y^{rms}, because the vertical emittance is not beam-beam limited and the effect of a given D_y^{rms} on the emittance scales with E^2. Also the coupling from the experimental solenoids scales with 1/E. Figure 4 shows the simulated dependence of vertical emittance on D_y^{rms}. Typical measured values are indicated by the grey bands, showing that D_y^{rms} was reduced from ~3.5 cm in 1998 to ~1.5 cm in 1999. The evolution of the vertical emittance in 1998 and 1999 is shown in Figure 5 for bunch currents of 500-550 μA. As expected it was significantly improved due to the reduction in dispersion. The vertical emittance reached its smallest value at 101 GeV, corresponding to an emittance coupling of 0.5%.

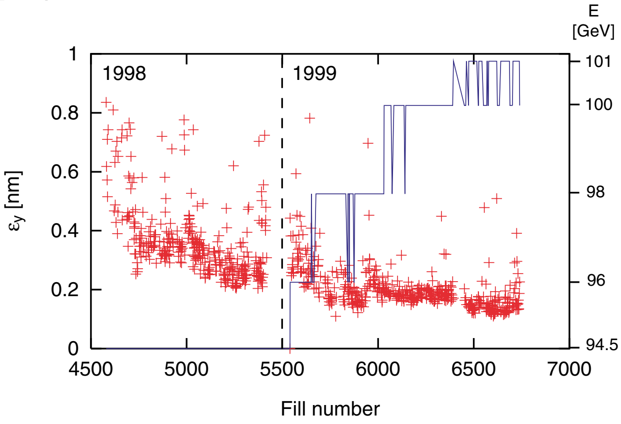

Figure 5: Evolution of vertical emittance during 1998 and 1999 for bunch currents of 500-550 μA. The line indicates the beam energy.

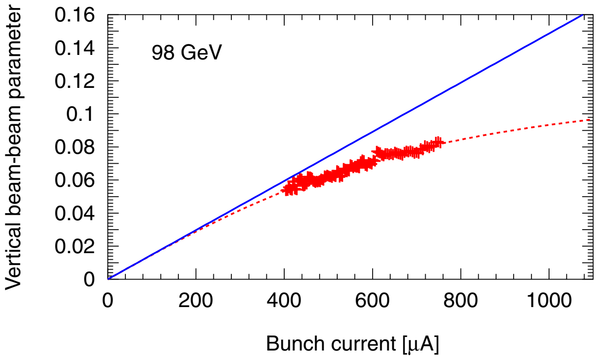

Figure 6: Vertical beam-beam parameter versus bunch current. The data is compared to the not beam-beam limited case and a fit [4].

Table 3: Average overhead per physics fill.

Year	Overhead per fill
1998	110 min
1999	93 min
2000	69 min

Luminosity monitoring for empirical fine tuning of orbit, coupling, and dispersion was improved by using the current lifetime during collision (~5 h for best performance) as a measure of luminosity [6]. A luminosity resolution of 2% was obtained on a 30 s running average.

A higher beam-beam limit for the high energy LEP results from the strong transverse damping (60 turns at 104.4 GeV compared to 721 turns at 45.6 GeV). Figure 6 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 [6]. From the fit we can infer a beam-beam limit at ξ_y =0.115 and an unperturbed vertical emittance of 0.1 nm. Though there is an emittance blow-up of up to ~70%, LEP did not reach the beam-beam limit at 98 GeV.

The strong transverse damping allows jumping the third integer resonance for a high Q_x working point of 0.36 (better luminosity and backgrounds) and energy ramping of the two beams in collision.

3.2 Improvements for integrated luminosity

The integrated luminosity is being optimised by maximising the instantaneous luminosity and the time available for physics. LEP operation includes a significant overhead due to the cycling of the machine, injection at 22 GeV, ramping to high energy and setting up for physics (orbit, collimators,…). As shown in Table 2, the overhead has been reduced from 110 min in 1998 to 69 min in 2000. Higher beam intensities from the injector chain, increased injection efficiency, and double ramp speed contributed to this important improvement.

In addition, efforts were made to reduce beam losses. An automated control of the horizontal damping partition number J_x as a function of the available RF voltage ensures appropriate levels of RF voltage overhead. The RF voltage overhead is optimised in 2000, as the operational beam energy follows the available RF voltage.

5 CONCLUSIONS

The operation of the LEP collider has been extended to 104.4 GeV maximum beam energy. Above 98 GeV operation has been optimised to achieve maximum beam energy. A different balance in the trade-off between luminosity and beam energy resulted in best performance at 98 GeV and somewhat reduced luminosity production above. A maximum beam-beam tune shift of 0.083 per interaction point was achieved with improvements in orbit, dispersion and coupling correction, in luminosity monitoring, and in the tune working point. The beam-beam limit was not reached, though some beam-beam blow-up is being observed. The operational overhead per physics fill was reduced from 110 min in 1998 to 69 min in 2000, maximising the time available for physics.

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