Three Years Operational Experience with LEP

R. Bailey, T. Bohl, F. Bordry, H. Burkhardt, K. Cornelis, P. Collier, B. Desforges, A. Faugier,
V. Hatton, M. Lamont, J. Miles, G. de Rijk, H. Schmickler
CERN, CH-1211 Geneva 23, Switzerland

Abstract

On July 14, 1989 a beam of positrons was injected into LEP from the SPS and completed the first full turn. One month later all 4 experiments, ALEPH, DELPHI, OPAL and L3 detected their first Z^0 particles. From September to December 1989, the machine was operated in a mixed mode of machine studies and operation for physics, at the end of which time a total of integrated luminosity of over 1.3 inverse picobarns had been recorded per experiment, resulting in a total of over 70,000 Z^0's detected. At the request of the physicists, the energy of each fill was varied, half the number of fills were at the Z^0 peak, the rest at $\pm 3, \pm 2, \pm 1$ GeV around the peak energy. In 1990 LEP was operated in the same way as in 1989 from March to July producing 12.3 inverse picobarns and three quarters of a million Z^0's. In 1991 operation continued in a similar way with initial luminosities reaching $10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and over 6,000 Z^0's per day in each experiment.

This paper summarises the experience over the first years of LEP operation giving typical and peak performance figures.

1 Introduction

In the summer of 1989, the four LEP experiments ALEPH, DELPHI, L3 and OPAL detected their first Z^0's. Since then the average number of Z^0's detected in each experiment per scheduled day of operation for physics has doubled each year, with 930 per day in 1989, 2310 in 1990 and 4740 in 1991. Peak performance figures indicate a steady improvement during the three years, although the difference between 1990 and 1991 was small. Average filling times have decreased, indicating a general improvement in operational efficiency, though equipment failures and problems related to the partial non-reproducibility of the machine at 20GeV, are still a matter for concern.

This paper summarises the experience of LEP operation for physics over the last three years, giving performance figures and highlighting particular operational challenges.

2 Filling LEP

Electrons and positrons are supplied by the SPS at 20GeV in 4 batches of 4 bunches during a 4.8 seconds slot in the 14.4 seconds SPS supercycle (the remaining 9.6 seconds being used for a 450GeV proton fixed-target cycle). In 1991 typical intensities of almost 1.5×10^{10} particles per bunch were obtained, a factor 2 higher than in previous years. This improvement was due to bunch lengthening at 3.5GeV in the CPS and supression of a fast vertical instability at about 12GeV in the SPS.

Accumulation in LEP is achieved by stacking in betatron space, with the injection points located in regions of minimum, but nonzero, dispersion [1]. The best accumulation rate is about 0.3mA per minute which is achieved by carefully optimising the injection parameters. Precise control of the closed orbit, the injection trajectories and longitudinal RF phase is required to maximise the available aperture[2, 3].

An increase in the average beam current at 20GeV was obtained in 1990 by using longer bunches from the injectors and a new working point in LEP. Since then, only a small improvement has been obtained and the *average* total current is about 3.5mA in the two equalised beams, compared to the design value of 6mA. At least two main effects limit the intensity and they occur simultaneously. Early in 1991 the operators developed the habit of lowering the chromaticities towards zero to obtain satisfactory accumulation. Subsequent observation of the bunches using the streak camera [4] revealed strong head-tail motion and the modes were frequently seen in the tune FFT spectrum. The second effect is due to residual long range beam-beam modes, which became more apparent in 1991 after the previous optics $Q_x, Q_y = (71, 77)$ was abandoned in favour of $Q_x, Q_y = (70, 76)$ [5]. Their presence reduces the freedom the operators have to steer the working point in-between synchro-betatron resonances, with the expected result that the accumulated intensity with two beams is less than twice the single beam intensity. Two attempts were made in 1991 to reduce the magnitude of these modes. The machine optics was recomputed to give a factor of 2 lower β_x^* thus reducing the horizontal beam-beam strength parameter [6, 7]. In addition the vertical beam separation was increased from 1.7mm to 2.1mm, though no clear improvement was observed. Studies on intensity limitations in LEP are on-going [8].

Ramping the beam from 20GeV to physics energies close to the Z^0 peak takes about 7 minutes, although this could be reduced significantly if required. This phase of operation is delicate and often results in beam loss unless the tunes, chromaticities and orbit are controlled precisely. Excessive excursions in tune can bring the beams onto synchro-betatron resonances, while chromaticity variations can provoke head-tail instabilities on modes $m = \pm 1$ (positive excursions) or on mode $m = 0$ (negative excursions). The settings files which define the ramp, are based on theoretical values computed offline by MAD [9, 10]. These settings are optimised by the operators using measurements made during machine developement sessions and previous physics runs. Machine reproducibility is one of the main preoccupations of the operations crews [11, 12]. The transverse tune feedback loop which was developed and used successfully during the first two years of LEP operation, did not function effectively in the horizontal plane in 1991. The tunes are tracked by a phase locked loop (PLL) whose dynamics are a compromise between the need for a large capture range and good tracking ability. Unfortunately the present PLL is confused by strong horizontal beam-beam modes which are driven by the even integer horizontal tune [13].

Until recently the optics at the end of the ramp was the same as at injection, with $\beta_y^* = 21$cm. The β_y^* was then reduced or "squeezed" at the even interaction points to ensure maxi-

Table 1: Comparison of LEP performance during the last three years.

		1989		1990		1991		
Total time scheduled	h		3107		3433		4002	
Time scheduled for commissioning	h		1284		0		0	
Time scheduled for setting-up	h		48		240		243	
Time scheduled for MD	h		454		689		997	
Time scheduled for physics	h		1321		2504		2762	
Time with beam in coast	h		469		1048		1242	
Efficiency (coast/physics time)	%		35		43		45	
		Peak	Average	Peak	Average	Peak	Average	Design
Total current accumulated 20 GeV	mA	2.85	2.20	4.20	3.10	4.30	3.50	6
Current in collisions 45 GeV	mA	2.64	1.66	3.60	2.50	3.70	2.80	6
Calculated initial luminosity	$cm^{-2}s^{-1} \times 10^{30}$	4.25	1.59	11.00	5.10	13.00	7.00	16
Integrated luminosity detected	pb^{-1}		1.7		8.0		17.3	
Integrated lum./scheduled day (physics)	nb^{-1}		31		77		158	
Beta at the experiments (V)	cm	7	7	4.30	7 and 5	4.30	7 and 5	7
Filling time	hh:mm	0:50	7:35	1:20	6:57	1:25	3:08	
Coast duration	hh:mm	12:45	5:00	22:35	7:30	27:00	8:00	
Total number of coasts			97		143		154	
Percentage of coasts lost	%		35		33		36	

mum luminosity for physics. During the first two years of LEP operation the nominal optics for physics achieved $\beta_y^* = 7$cm, frequently 5cm and occasionally 4.3cm. In preparation for the squeeze, the standard procedure after ramping was to tune the machine very carefully. This time-consuming process was eliminated by combining the ramp and squeeze, and after a great deal of preliminary work [7] the procedure became fully operational in October last year. However, tuning is still required after the squeeze to prepare the machine for physics.

3 Machine Performance for Physics

Each year since 1989 the integrated luminosity per scheduled day of operation for physics has doubled. The records at the end of 1990 (Fig. 1) showed a large difference in the integrated luminosity seen by each experiment and this was partly explained when inspection of the superconducting quadrupoles (QSC's) on each side of the low-beta interaction points revealed that they were misaligned inside the cryostat. A decision was taken at the beginning of 1991 to try to improve the luminosity for physics by introducing a new optics. The tunes which were chosen $Q_x, Q_y = (70, 76)$ were expected to be good for polarisation and were not too far from the pretzel tunes. Initial performance at the start of 1991 was disappointing until the low-beta optics was measured and a $\beta_y^* = 8$cm was found, instead of the nominal 5cm. A correction to the strength of the QSC's was made and it became possible to run the machine with $\beta_y^* = 5$cm and even $\beta_y^* = 4.3$cm on a regular basis. Subsequent analysis revealed that the problem was due to a change in the strength of the main bending field, probably due to ageing in the concrete/iron magnets [14].

In common with other electron machines [15], good vertical orbit control is essential to achieve high luminosities and acceptable background levels at top energy. As is well known [16], the effect of coupling together with the influence of the vertical closed orbit on residual vertical dispersion, have a strong impact on vertical emittance. The notion of "Golden Orbits", which provide short-term reference points for good operation, was invoked in 1990 with some success, though used to a lesser extent in 1991. Empirical application of antisymmetric orbit bumps around the even interaction points (thereby including the QSC's, $\beta_y \approx 400$m) was also used operationally with success. Closed orbit monitoring and control is one of the main activities of the operations crews during production coasts.

At the beginning of a fill with currents of 2 mA/beam and standard 1991 conditions ($\epsilon_x = 35$nm and $\sigma_x \gg \sigma_y$ at 45.625 GeV) the horizontal tune shift $\xi_x = 0.04$ is considered to be rather big and substantially reduces the choice of good tune values [17]. The vertical beam-beam parameter depends on β_y^* and can be estimated from the observed luminosity. Analysis of performance data shows that ξ_y was significantly higher in 1991 with typically $\xi_y \approx 0.02$ compared to an average $\xi_y \approx 0.015$ in 1990. This improvement followed the change in optics mentioned above. The overall performance during the last three years is summarised in Table 1.

Operation during the last two years featured several "Energy Scans". At the request of the physicists, the "production" energy of each fill was varied, sometimes above the Z^0 peak, otherwise below. Each run off peak was followed by a run back on the peak. The energy range 44.125GeV to 47.125GeV has been covered and the integrated luminosities are summarised in Fig. 2 (interlaced scans 1990/1991).

4 Interruptions to Normal Operation

There are three types of interruptions to normal operation that reduce the operational efficiency of any collider; the first type results in the loss of fills, the second type causes many hours delay between filling, and the third type short duration perturbations. In 1989, 1990 and 1991, 35% , 33% and 36% respectively of all fills were lost due to equipment faults. Power converter trips are frequently associated with cooling problems or transients on the mains, often as the result of thunderstorm activity. Throughout 1990, trips in one or more of the RF units were a feature of LEP operations. The RF improved in 1991 and the two major sources of down time were firstly a series of problems in the 15 year-old SPS electrical distribution system during the summer and secondly a leak in the DELPHI vac-

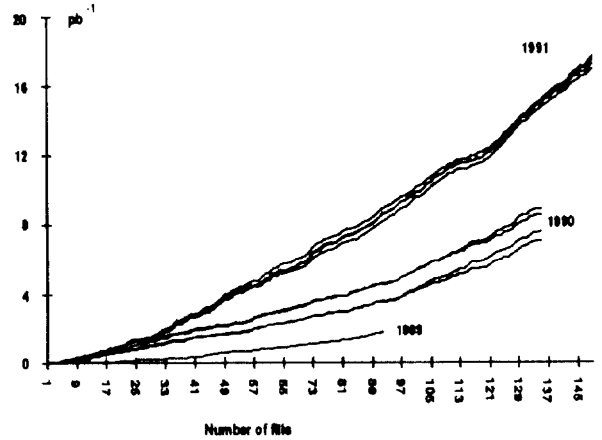

Figure 1: Integrated Luminosity seen by ALEPH, DELPHI, L3 and OPAL

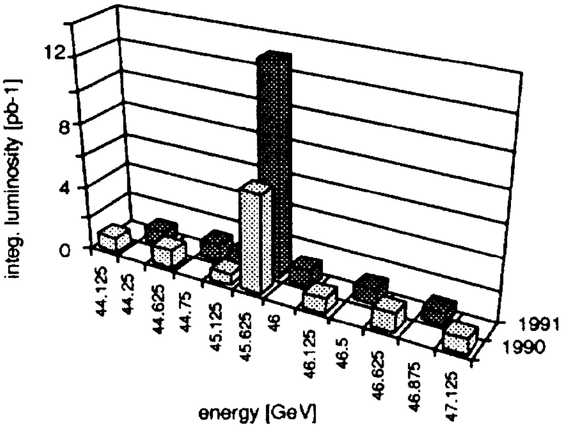

Figure 2: Energy Scans : 1990 and 1991

uum chamber which occured in October. Precise accounting of down time and fault reporting is one the most important activities of the operations crews as it provides the statistics the hardware specialists need in their equipment improvement programs. This policy has already resulted in a significant increase in the reliability of the beam orbit monitor (BOM) system during 1991.

5 Combined SPS and LEP Operations

It was decided early in the LEP project that the machine should be operated from the SPS control building by the SPS operations group. This has proved to be very successful. The LEP primary services, which include electricity, water, ventilation, cryogenics, vacuum and others, were also supervised from the same building during the commissioning period and the first year of operation. They are now under the responsability of the CERN General Services control room.

Machine development sessions, which constitute 25% of the LEP running schedule, are carried out by members of the machine physics group, closely supported by the operations crews. During these sessions the regular operation of the SPS continues unperturbed. In the same spirit, the crews organise LEP filling and running to accomodate machine development sessions in the SPS and thus avoid unnecccessary perturbation to the LEP physics program. The statistics show that there has been no measurable reduction in the efficiency of operation of the SPS during operation of LEP.

6 Acknowledgements

The operation of LEP depends on the close collaboration of the SPS/LEP control room crews, the equipment specialists, the machine physicists and the experimental physicists for whom the machine runs. The success also depends on the skill and expertise of the physicists and engineers of the CPS complex. The authors would like to thank all those concerned.

References

[1] *LEP Design Report, Vol.2, The LEP Main Ring*, CERN LEP/84-01, (1984).

[2] K. Hübner *et al.*; *Dynamic Aperture at Injection*, LEP Performance Note 20, CERN, Geneva, (1989).

[3] J. Miles *et al.*; *Dynamic aperture at injection energy (20 GeV)*, LEP Performance Note 30, CERN, Geneva, (1990).

[4] E. Rossa *et al.*; *Double Sweep Streak Camera for LEP*, Proc. of the 2nd European Particle Accelerator Conference, Nice, (1990).

[5] E. Keil; *Conclusions from the optics session* , Proc. of the 1st Workshop on LEP Performance, ed. J. Poole, CERN SL/91-23(DI), CERN, Geneva, (1991).

[6] E. Keil; *Frequencies of Coherent Beam-Beam Modes* , LEP Performance Note 58, CERN, Geneva, (1991).

[7] A. Hofmann; *Low β_x^* Injection and Combined Acceleration and Squeeze*, LEP Performance Note 69, CERN, Geneva, (1991).

[8] J. Gareyte; *Intensity Limitations*, Presentation 1, Proc. of the 2nd Workshop on LEP Performance, ed. J. Poole, CERN SL/92-XX(DI), Geneva, (1992).

[9] Y. Marti *et al.*; *Production and Use of New LEP Optics*, LEP Performance Note 23, CERN, Geneva, (1990).

[10] Ch. Iselin *et al.*; *Implementation of the LEP Optics Model*, Proc. of the 2nd European Particle Accelerator Conference, Nice, (1990).

[11] T. Bohl; *Reproducibility of LEP*, Presentation 33, Proc. of the 1st Workshop on LEP Performance, ed. J. Poole, CERN SL/91-23(DI), CERN, Geneva, (1991).

[12] P. Collier; *Orbit Corrections During LEP Acceleration*, LEP Performance Note 65, CERN, Geneva, (1991).

[13] H. Schmickler; *Residual Beam-Beam Effect* , Presentation XX, Proc. 2nd Workshop on LEP Performance, ed. J. Poole, CERN SL/92-XX(DI), Geneva, (1992).

[14] J. Gascon *et al.*; *The temperature dependence of the energy calibration of LEP beams by flux loop measurements*, LEP Performance Note 74, CERN, Geneva, (1991).

[15] Y. Funakoshi *et al.*; *Luminosity tuning in TRISTAN main ring*, 2nd European Particle Accelerator Conference, Nice, France, pp. 59-64, (1990).

[16] T. O. Raubenheimer and R. D. Ruth; *Analytic estimates of coupling in damping rings*, SLAC PUB 4914, Stanford, (1989).

[17] H. Burkhardt *et al.*; *The Effect of the Beam-Beam Interaction on the Performance of LEP*, Proc. of the 3rd European Particle Accelerator Conference, Berlin, (1992).