TWELVE YEARS OF LEP

M. Lamont for the LEP team, CERN, Geneva, Switzerland

Abstract

LEP was commissioned in 1989 and closed down in November 2000. During this time it has operated in many different modes, with many different optics and at many different energies. Performance has varied. LEP has provided a huge amount of data for the precision study of the standard model, first on the Z^0 resonance, and then above the W pair threshold. Finally, with beam energies above 100 GeV, a tantalising glimpse of what might have been the Higgs boson was observed. A history of the main modes of operation, associated performance and the challenges met over the 12 years of running is presented.

1 LEP MACHINE MODES

Year	Optics	Comment	Bunch Scheme
1989	60/60	LEP commissioned	4 on 4
1990	60/60		4 on 4
1991	60/60	90/90 tested	4 on 4
1992	90/90	Pretzel commissioned	4 on 4/Pretzel
1993	90/60		Pretzel
1994	90/60		Pretzel
1995	90/60	Tests at 65-68 GeV	Bunch trains
1996	90/60	108/90 tested	4 on 4
1997	90/60	108/90 & 102/90 tests	4 on 4
1998	102/90		4 on 4
1999	102/90		4 on 4
2000	102/90		4 on 4

Optics, main modes of operations and bunch scheme from 1989 to 2000.

2 COMMISSIONING

Commissioning started on the 14th July 1989 with the first beam injected into the machine, by 23rd July circulating beam had been established, by 4th August a single beam had been taken to 45 GeV. The first colliding beams were established on the 13th August with the first Z boson seen shortly after.

3 THE EARLY YEARS

The first full year of operations was 1990 and life was a bit of a struggle. Total beam current was around 3 mA and peak luminosity only $2\text{-}3\times10^{30}\text{cm}^{-2}\text{s}^{-1}$. The optics used had a 60° phase advance in both planes and beam sizes were revealed to be large. Worries reflected in the proceedings of the post run Chamonix meeting included: development of a new optics (still 60° but with different integer tunes), vertical dispersion, dynamic aperture, closed orbit, intensity limitations at injection, longitudinal oscillations and beam-beam. The Pretzel scheme, which was to increase the number of bunches to 8 per beam, was already under consideration.

The struggles continued in 1991, when operations were wrestling with, among other things, the control system and beam losses in the ramp. Tests with the variant 60°/60° optics were made and a first tests of the Pretzel scheme, and of an optics with a 90° degree phase advance, were made.

1992 saw the introduction of a new suite of high-level software and an attempt to use a 90°/90° optics with a combined ramp & squeeze (in which the β_y squeeze is performed during the energy ramp, rather than after it). The start-up was an unmitigated disaster, with the conclusion being reached that the 90°/90° optics was unstable; the combined ramp and squeeze was abandoned. A switch back to the 60°/60° optics went somewhat more smoothly. Later in the year 90°/90° was tried again and worked. Pretzel was commissioned.

4 Z^0 PRODUCTION

By 1993 things had started to settle down, the control system was eventually taking shape, the optics was now 90°/60° and Pretzel was operational. During the 1992 to 1993 shutdowns there had been a major realignment of the machine and this had clearly helped improve the performance. Design luminosity was reached in one experiment on the 31st May. Luminosity production took place at a variety of energies as the Z^0 resonance was scanned. Bunch train machine development provided an interesting backdrop.

1994 continued with Pretzel and 90°/60° and very respectable luminosity production, with beam-beam tune shifts of up to 0.047. Synchrotron injection was commissioned. Bunch train tests continued and the search for a high-energy optics was started with a first look at 108°/60° being made. A high-energy optics was required because of the increase in horizontal emittance with energy: it was predicted that the 90°/60° optics would run out of dynamic aperture at high energy.

With things going so well, the obvious thing to do in 1995 was to try bunch trains; the original plan being to collide trains of 4 bunches per train. Operationally this proved very difficult with beam break-up and parasitic beam crossing limiting the intensities that could be accumulated and ramped. Eventually 3 bunches per train became operational. The injection energy was raised to 22 GeV to boost the bunch current limit. Test on potential high-energy optics (108°/60° and 108°/90°) continued.

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The first superconducting RF cavities had been installed and in November 1995 physics at 65 and 68 GeV was successfully delivered

5 1996: TRANSITIONAL YEAR

Two Heineken bottles left in the vacuum chamber made for an interesting but frustrating start-up. The main aims of the year were to establish the RF system, deliver a reasonable amount of luminosity above the W pair threshold and confirm the choice of high-energy optics. The year started with high-energy candidate 108°/60°. However, attempts to do physics at 45 GeV (Z^0s were required by the experiments at the start of each year to calibrate their detectors) with this low emittance optics proved difficult. Aperture searches reveal nothing and giving way to what looked like low dynamic aperture, the switch back to 90°/60° was made. Things progressed smoothly and operations at a beam energy of 80.5 GeV, just above the W pair threshold, was established. At the end of the year there was an extended test with the 108°/90° optics, luminosity was produced but the performance was below that of the 90°/60° optics.

6 HIGH ENERGY RUNNING

Start-up 1997 was delayed by the recovery from a major fire in one of the surface buildings of the SPS. Nonetheless a reasonable year with the energy pushed to 91.5 GeV. With the high beam energies synchrotron radiation had started to cause problems with vacuum leaks a major problem throughout the year. While operating with 90°/60°, 108°/90° investigations confirmed the large de-tuning expected from this optics and a possible explanation for the poor performance. In the mean time, a 102°/90° was developed and a week long test with this at the end of the year was very successful and the search for a high-energy optics was over.

Staged installation of more superconducting cavities was taking place during the annual shutdowns and in 1998 the energy was pushed to 94.5 GeV and despite problems in the ramp caused by HOM heating of RF antennae cables, performance was excellent, with instantaneous luminosity of up to 10^{32}cm-2s-1 and record beam-beam tune shift of up to 0.075.

This trend continued with another record year in 1999 with luminosity production at 98, 100 and 101 GeV and beam-beam tune shifts of up to 0.083. After 10 years operations had finally mastered the machine and the main concern was continual, painstaking tuning and maintenance of the now huge superconducting RF system.

7 2000: PUSHING THE LIMITS

There was very little additional RF installed between 1999 and 2000, but there was the exhortation from the physics community to maximise the Higgs reach which meant delivering a sizeable amount of luminosity at the maximum possible energy. A very concerted effort was made which included pushing the RF system to its limit, reducing the RF frequency (buying increase energy damping and thus RF volts), using the orbit correctors as bending magnets, and an operational strategy which involved changing the energy of the beam during a physics fill. The result was a resounding success with luminosity delivered up to a maximum energy of 104.5 GeV. A total of 233 pb^{-1} was delivered of which 131 pb^{-1} was between 103 and 103.5 GeV, with 10.7 pb^{-1} over 104.0 GeV, this enabling the highest possible limits to be set in chargino searches.

The delivered luminosity allowed the limit on the Standard model Higgs mass to be pushed further than expected, and in June 2000 Aleph observed a high signal-to-background four jet Higgs candidate with a mass around 115 GeV/c^2. As the year progressed the strength of their signal at this mass continued to grow, and the excess reported by Aleph in September 2000 motivated the demand for a 2 month extension by the LEP experiments. In the end a total 6 weeks extension was granted, and subsequently Higgs candidates were also seen by other experiments in other channels. A combined excess of 2.9 σ with respect to the background only hypothesis was reported at the end of the 2000 run. A very vocal request to run in 2001 provided management with a keen dilemma, squeezed as CERN was by the tight LHC schedule. The decision to close LEP for good was announced on the 8th November.

8 PERFORMANCE

Performance naturally divides into two regimes: 45 GeV running around the Z boson resonance and high energy running above the threshold for W pair production.

The performance at 45 GeV was very much constrained by the beam-beam effect, which limited the bunch currents that could be collided. The beam-beam effect blew up beam sizes and the beam-beam tune shift saturated at around 0.04. Optimisation of the transverse beam sizes was limited by beam-beam driven effects such as flip-flop. Operationally life was a struggle as the hard beam-beam limit was constantly probed. The main breakthrough in performance at this energy was an increase in the number of bunches: first with the Pretzel scheme (8 bunches a beam) commissioned in 1992, and then with the bunch train scheme (up to 12 bunches per beam) used in 1995. Both schemes reduced the bunch current that was collided and also the resultant beam-beam tune shift. This was attributed to effects of parasitic long-range encounters. The increase in number of bunches, however, provided a net gain.

Between 1996 and 2000 the beam energy was progressively increased from 80.5 to 103 GeV by installing more RF cavities and increasing the accelerating gradients. At these energies beam oscillations are strongly damped and the single particle motion has an important random walk component due to the large number of emitted photons. Consequently particles no longer lock on higher-order resonances driven by the non-linear beam-beam force and beam size blow up is reduced allowing the use of higher bunch currents. Record beam-beam tune shifts of about 0.08 were achieved. Bunch trains were ruled out by the total beam current limit imposed by the RF system. A summary of the performance through the years is shown in table 2.

Year	∫L [pb^{-1}]	Beam Energy [GeV]	Total Current [mA]	Peak Lumi. [10^{30} $cm^{-2}s^{-1}$]	Max. ξ_y
1989	1.74	45.6	2.6	4.3	0.017
1990	8.6	45.6	3.6	7	0.020
1991	18.9	45.6	3.7	10	0.027
1992	28.6	45.6	5.0	11.5	0.027
1993	40.0	45.6	5.5	19	0.040
1994	64.5	45.6	5.5	23.1	0.047
1995	46.1	45.6	8.4	34.1	0.030
1996	24.7	80.5-86	4.2	35.6	0.040
1997	73.4	90-92	5.2	47.0	0.055
1998	199.7	94.5	6.1	100	0.075
1999	253	98-101	6.2	100	0.083
2000	233.4	102-104	5.2	60	0.06

Table 2: Performance of LEP from 1989 to 2000

9 ENERGY CALIBRATION

Although well documented elsewhere (see for example refs 123), no resume of LEP operation would be complete without mention of the achievements of the energy working group, responsible as they were for the precise determination of the beam energy throughout the lifetime of the machine. The determination of the standard electroweak parameters such as m_Z and Γ_Z require a precise knowledge of the centre-of mass energy at the collision points. Precise energy calibration can be performed using resonant depolarisation. This can only be done during dedicated experiments with single beam. The challenge lied in understanding the factors that affect the beam energy, developing a model and then using this model and magnet measurements to extrapolate between resonant depolarisation measurements. Best possible estimates of the energies over 15 minutes intervals were given to the LEP experiments for data analysis. The final result was a systematic error due to the energy calibration of the LEP beams of only 1.7 MeV on m_z and of 1.3 MeV on Γ_Z.

At LEP2 a direct energy calibration by resonant depolarisation is not possible because transverse polarization does not build up at such high energies. The beam energy is established by extrapolation from measurements performed at lower energies, cross-calibration with measurements from NMR probes installed in the dipoles, and NMR measurements made at physics energy.

10 RF

The move to centre-of-mass energies above the W pair threshold was originally foreseen in the original LEP design proposals. A program of research and development into the use superconducting RF technology was initiated. This was not without challenges, but eventually the program led to industrial production. Staged installation from 1995 to 1999 allowed a corresponding increase of the beam energy. The last superconducting modules were installed in the shutdown between 1999 and 2000. The modules ended up performing at field gradients well above nominal and, together with some operational tricks, allowed the beam energy to be pushed to 104.4 GeV, well above even the most optimistic estimates. The final complement of superconducting RF was 288 cavities driven by 36 klystrons. In the final year of LEP operations the RF system consistently delivered a total voltage around 3650 MV: a truly remarkable achievement.

11 CONCLUSIONS

LEP was always interesting. The challenges were ever present, from commissioning, the choice of optics, the introduction of ambitious multi-bunch schemes, first Pretzel and then bunch trains. There then followed the move to high energies, more new optics, the technological challenges of the superconducting RF system and the effort required to keep the whole system running at way above design, the problems of synchrotron radiation and the pleasures of moving into the ultra strong damping regime where high bunch currents could be collided with impunity.

At the end of the day, LEP had delivered over 200 pb^{-1} around the Z^0 resonance, over 700 pb^{-1} over the W-pair threshold. This corresponds to over four million Z bosons and around ten thousand W boson pairs per experiments. The precision of the LEP beam energy was reduced by more than one order of magnitude with respect to original estimates using resonant depolarisation. These results have allowed the standard model to be tested with incredible precision. It can be claimed that it is no longer the standard model but now the standard theory.

12 ACKNOWLEGMENTS

The 12 years of LEP operations represent a truly remarkable effort on behalf of all involved.

13 REFERENCES

Constraints on space mean forgoing a full list of references; the following provide good jumping off points.

[1] D. Brandt, H. Burkhardt, M. Lamont, S. Myers, J. Wenninger,"Accelerator Physics at LEP", Reports on Progress in Physics", vol. 63, No. 6, June 2000.
[2] Proceedings of the LEP performance workshops, Chamonix, 1991 to 2001