

# LEP1 operation, 1989-1995

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## Abstract

In October 1995 the last run foreseen for dedicated Z production at CERN was performed in LEP, thereby bringing to a close the first phase of operation of this machine. A total luminosity of  $200 \text{ pb}^{-1}$  has been delivered to each of the four experiments, which together have recorded the decays of over 20 million Zs. Machine performance has increased to the extent that a good weekend in 1995 saw as much luminosity delivered as in the whole of 1989. This improvement has been made possible by a combination of several things. Over and above general operational expertise, special care went into the treatment and stabilisation of the closed orbit in order to obtain reproducible high performances with vertical beam-beam tune shifts exceeding values of  $\xi_y = 0.04$ . Both Pretzel and Bunch Train schemes have been introduced to double the number of bunches, and high-tune optics have been developed to produce low transverse emittances which allow operation at the beam-beam limit throughout physics runs. Included in the integrated luminosity are data taken off the peak of the Z resonance, to allow precise determination of the mass and width of this particle. Accurate measurements of the beam energy during these runs have brought to the fore some unusual effects.

## 1 FILLING AND PREPARATION FOR PHYSICS

For LEP operation with 4 bunches per beam, the SPS delivered two batches of 4 positron bunches and two batches of 4 electron bunches in a 4.8s slot in the supercycle used also for physics with proton or ion beams. When LEP moved to 8 bunch Pretzel operation, the injection scheme was modified to deliver 8 bunches of each particle type in a shorter time in the SPS supercycle. This did not contribute to a faster filling of LEP but liberated time for other purposes in the SPS. With the move to the 4 bunch train scheme, the 8 bunch mode was preserved in the SPS, using synchrotron injection to stack into 4 bunches in LEP. Different bunches of a train were filled using subsequent SPS supercycles with appropriate time delays for injection into LEP. Bunch intensity equalisation was achieved in all modes by automatically disabling the SPS extraction kicker for individual bunches that had already reached the desired intensity. LEP1 has been limited by the currents per bunch that can safely be collided rather than by the currents that can be accumulated [1]. Limitations at injection were not a performance limitation at LEP1, but are expected to be important for LEP2, where the rela-

tive decrease of the beam-beam effect with energy should allow much higher currents in collision. In 1995 the injection energy was raised to 22 GeV and the mode of injection changed from betatron to synchrotron injection [2].

The filling conditions for LEP were quite reproducible and currents of 0.30 mA per bunch can usually be reached with no or only minor adjustments. Small, positive chromaticities, very similar currents in all bunches and a longitudinal feedback system using a dedicated cavity operating at a frequency of 1 GHz, were important to accumulate currents beyond 0.30 mA per bunch in the case of two beams and 8+8 or more bunches.

The main changes in the procedures for filling and preparation for physics were the increase in the number of bunches from 4+4 to 8+8 in the Pretzel scheme [3] and a further increase in the number of bunches in 1995 with the bunch train scheme[4].

Damping, emittance and polarisation wigglers are installed in LEP. The damping wigglers are operated in a dispersion free region. They are fully excited at injection to reduce damping times and to lengthen the bunches from 0.3 to 1.2 cm. A further increase in bunchlength from 1.5 to 2 cm is possible using the emittance and polarisation wigglers and has been used for part of the LEP1 operation. The synchrotron tune at injection was typically  $Q_s=0.085$ .

The preparation for physics proceeds through several steps. Ramping from injection to physics energy takes about 6.5 minutes. The change of optics, reducing the vertical beta function from 21 cm to 5 cm for physics, is done in about 1 minute.

The initial working point for physics is typically chosen with fractional parts of the tunes as  $Q_x=.30$ ,  $Q_y=.16$  and  $Q_s=.065$ . Orbits are corrected and the emittance wiggler is turned on to maximum excitation before beams are brought into collision. The wiggler increases the horizontal emittance from 12 to 36 nm and avoids excessive beam-beam effects. For currents of 0.35 mA per bunch and 36 nm emittance, the horizontal tune shift is limited to a value of 0.028.

The physics coast is declared from the moment that collimators have been moved to tight physics settings. Background conditions for the experiments have generally been very good, which was useful for example to reach precision in the luminosity measurements to levels of order  $10^{-3}$ .

## 2 PERFORMANCE FOR PHYSICS

The luminosity produced in LEP1 operation per year is shown in fig. 1. The luminosity numbers are always given

|  | 1990      |      | 1991        |      | 1992    |      | 1993  |      | 1994  |      | 1995  |      |
|--|-----------|------|-------------|------|---------|------|-------|------|-------|------|-------|------|
| Hours scheduled for physics                      | 2504      |      | 2762        |      | 3439    |      | 2943  |      | 3175  |      | 3070  |      |
| Hours scheduled for M.D.                         | 689       |      | 997         |      | 935     |      | 709   |      | 867   |      | 685   |      |
| Hours of beam in physics                         | 1048      |      | 1242        |      | 1742    |      | 1619  |      | 1871  |      | 1414  |      |
| Efficiency                                       | 43 %      |      | 45 %        |      | 51 %    |      | 55 %  |      | 59 %  |      | 46 %  |      |
| Integrated luminosity, $\text{pb}^{-1}$          | 7.6       |      | 17.3        |      | 28.6    |      | 40    |      | 64.4  |      | 46.1  |      |
| $\beta_x^*$ , m                                  | 1.25      |      | 1.25        |      | 1.25    |      | 2.5   |      | 2.0   |      | 2.5   |      |
| $\beta_y^*$ , cm                                 | 7, 5, 4.3 |      | 7.5, 5, 4.3 |      | 7, 5    |      | 5     |      | 5     |      | 5     |      |
| Total number of phys. fills                      | 143       |      | 154         |      | 199     |      | 168   |      | 197   |      | 194   |      |
| Percentage of fills lost                         | 33%       |      | 36%         |      | 36%     |      | 37%   |      | 23%   |      | 37%   |      |
| Horizontal Tune                                  | 71.3      |      | 70.3        |      | 94.3    |      | 90.3  |      | 90.3  |      | 90.3  |      |
| Vertical Tune                                    | 77.2      |      | 76.2        |      | 100.2   |      | 76.16 |      | 76.16 |      | 76.16 |      |
| Number of Bunches                                | 4+4       |      | 4+4         |      | 4+4,8+8 |      | 8+8   |      | 8+8   |      | 12+12 |      |
|  | peak      | avg. | peak        | avg. | peak    | avg. | peak  | avg. | peak  | avg. | peak  | avg. |
| Total cur. at inj., mA                           | 4.2       | 3.1  | 4.3         | 3.5  | 5.7     | 4.7  | 5.8   | 4.8  | 6.4   | 5.2  | 8.6   | 5.1  |
| Cur. in coll. at 45 GeV, mA                      | 3.6       | 2.5  | 3.7         | 2.8  | 5       | 4.2  | 5.5   | 4.4  | 5.5   | 4.8  | 8.2   | 4.5  |
| Vert.B.B. tune shift $\xi_y$                     | .025      | .017 | .032        | .02  | .037    | .025 | .037  | .027 | .045  | .034 | .030  | .023 |
| Luminosity, $10^{30}\text{cm}^{-2}\text{s}^{-1}$ |           |      |             |      | 10.9    |      | 15.9  |      | 20.5  |      | 20.4  |      |
| Turn around time, hours:min                      | 1:20      | 6:57 | 1:20        | 3:07 | 0:50    | 2:12 | 0:54  | 2:26 |       | 2:28 |       | 2:17 |
| Coast duration, hours:min                        | 22:35     | 7:30 | 27:00       | 8:00 | 26:30   | 8:35 | 9:40  |      | 9:30  |      | 9:30  |      |

Table 1: Comparison of LEP parameters and performance from 1990 to 1995

per experiment. The running of 1995 was devoted in parts

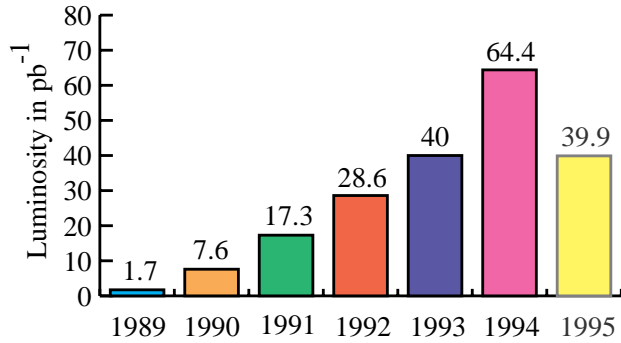


Figure 1: Integrated luminosity per year at Z-energies. Part of 1995 was already at higher energies, with another  $6.4 \text{ pb}^{-1}$  of luminosity produced.

to the running in of new superconducting cavities and to a first production at higher energies. A detailed comparison of LEP parameters and performance from 1990 to 1995 is given in table 1. For 1995, performance in terms of vertical beam-beam tune shift and peak luminosity is given for the running at LEP1 energies only. The efficiency is calculated from the time in physics (collisions, experiments taking data) compared to the total time including the time needed to prepare physics with accumulation, ramping, squeezing and downtime without beam. In 1993 and 1995, significant time was spent for energy calibration and the efficiencies would increase by about 5 % if this would be counted as time in physics.

We now comment some main changes that took place through the various years of LEP1 operation.

1989: The first running periods were relatively short and

luminosities typically  $2 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ . The  $1.7 \text{ pb}^{-1}$  delivered at beam energies between 44 and 47.5 GeV were however sufficient to give a first rich physics output including the determination of the number of neutrinos and the measurement of the Z-mass to about 50 MeV. A major concern was betatron coupling, introduced by a thin, magnetized nickel layer between the vacuum chamber and radiation shield.

1990: The 71/77 optics was introduced for lower coupling but turned out to be not so good for beam-beam. Some runs were already with  $\beta_y^*$  values below the design value of 7 cm.

1991: The 70/76 optics gave slightly higher beam-beam tune shifts. Energy calibration using resonant depolarization allowed a very precise energy determination.

1992: The phase advance was increased in both planes from  $60^\circ$  to  $90^\circ$ . This resulted in a decrease of the horizontal natural emittance from about 35 nm down to 12 nm. The emittance wigglers were used to increase the horizontal emittance if necessary. It became easy to operate LEP with constant beam-beam limit throughout fills lasting 10 hours in physics. Beam-beam tune shifts increased. In the last weeks of 4+4 operation, bunch currents of  $400 \mu\text{A}$  were safely collided and the vertical beam-beam tune shift exceeded regularly values of 0.03. Pretzel operation with 8+8 bunches was commissioned and quickly reached similar performance as the best 4+4 operation. The comparison of final 4+4 and first 8+8 running showed that both currents per bunch and beam-beam tune shift had decreased by about  $\sqrt{2}$  in Pretzel operation.

1993: LEP had been realigned and the optics was changed in the vertical plane to  $60^\circ$  to allow better orbit measurement and correction. Another precise energy scan

with frequent beam energy calibration by resonant depolarization was performed. Residual vertical and horizontal separation was minimized and allowed beam-beam tune shifts similar to the best 4+4 operation. Still, fills with similar currents resulted in luminosities and vertical beam-beam tune shift parameters  $\xi_y$  varying significantly ( $\pm 30\%$ ). Vertical orbit corrections had significant effects on luminosity. However, it was not sufficient to reach a small rms in the vertical orbit. Correcting back to the particular structure of a vertical orbit saved in a condition with excellent beam-beam tune shift ("golden orbit") gave reproducibly good results.

1994: Optics and running conditions were unchanged compared to 1993. Stable operation at one single beam energy and extensive use of reloading and reproducing "golden orbits" resulted in excellent and rather reproducible performance with vertical beam-beam tune shifts exceeding 0.04 on many occasions[6].

1995 saw the commissioning of bunch trains and superconducting RF and another energy scan with very frequent energy calibrations using resonant depolarization. The bunch train scheme allowed in principle to double the number of bunches to 16+16 bunches colliding in the four interaction regions. However it proved very difficult to control all unwanted collisions, and stable running conditions were achieved with 12+12 bunches. The total current in physics increased but it was not possible to exceed beam-beam tune shifts of 0.03 such that the luminosities were similar to the best Pretzel operation with 8+8 bunches. LEP1 operation stopped in October 1995. More superconducting RF cavities were installed. The beam energy was raised in November 1995 to 65-68 GeV, about half-way between LEP1 and LEP2 energies. Bunch currents of 500  $\mu\text{A}$  could be safely collided and record luminosities of  $2.5 \cdot 10^{31} \text{cm}^{-2} \text{s}^{-1}$  and tune shifts of 0.05 were achieved with collisions of only 4+4 bunches.

### 3 COMPARISON WITH SOME DESIGN PARAMETERS

The design luminosity for LEP1 energies of  $1.3 \cdot 10^{31} \text{cm}^{-2} \text{s}^{-1}$  was exceeded in 1993. The design was based on 4+4 bunches with 750  $\mu\text{A}$  current per bunch and a beam-beam tune shift of 0.03. Stable running with low backgrounds in LEP1 was much easier to achieve with lower bunch currents and doubling the number of bunches. The move to the high phase advance optics ( $90^\circ$  in the horizontal plane) with the low horizontal emittance of 12 nm allowed to work at the beam-beam limit throughout fills of typically 10 hours duration and down to bunch currents of about 150  $\mu\text{A}$ .

Beam lifetimes at LEP1 were about 50 hours for single beams and 20 hours for colliding beams or about three times longer than originally anticipated [5]. To a large extent, this is due to the excellent vacuum conditions in LEP but also due to an effective cutoff parameter that has to be taken into account for a realistic prediction of the cross-section in beam-beam Bremsstrahlung. The main lifetime limita-

tion for single or separated beams is Compton scattering of beam particles with thermal photons from the black body radiation of the beam-pipe.

Probably the most striking difference between expectations and achievements is the fantastic precision reached in the calibration of the mean energy of the beams circulating in LEP. A precision of 20 MeV in the measurement of the mass of the Z was hoped for, already assuming the possibility of resonant depolarisation of transversely polarized beams [7]. More than an order of magnitude higher precision has been achieved, revealing many subtle, often surprisingly small effects [8]: The tide effects of the moon and sun change the 27 km circumference of LEP by about  $\pm 1\text{mm}$  which is seen and corrected for. Leakage currents from the rails of trains passing near the LEP site tend to increase the dipole fields of LEP by small but non-negligible amounts.

## 4 CONCLUDING REMARK

The LEP machine ran very well at Z-energies, exceeding specifications - in case of the precision in beam energy determination even by an order of magnitude. Even if LEP1 can be considered a conventional machine, we found that operating and optimising it has been a very interesting and challenging experience.

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