PERFORMANCE OF LEP AND FUTURE PLANS

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Abstract The performance of LEP has been steadily improving: 750,000 Z^0 were produced in 1990. Many of the design parameters have been reached separately, showing that the machine behaves basically as expected. In fact, some design parameters have been exceeded (β^*, emittance ratio) and a significant level of polarization was obtained. An improvement by a factor of up to four in integrated luminosity is still to be expected by overcoming the identifiable limitations : strong synchro-betatron resonances and blow-up of the beam due to the beam-beam effect. Solutions to these problems have been devised and will be tested in a vigorous machine study programme. The long term LEP Experimental Programme has been defined by the physics community: a pretzel scheme will be installed to increase the luminosity. It will be followed by the LEP 200 programme to increase the energy up to and beyond the W pair threshold. The production and installation of the required superconducting cavities are in progress and due to be finished in 1994. An active programme of polarization studies is undertaken with the objective of precision measurement of Z^0 mass and width. The feasibility of spin rotators is being assessed to provide longitudinally polarized beams.

1 INTRODUCTION

After reviewing the performance achieved, this paper presents the phenomenology of the beam dynamics in LEP, the present understanding of its limitations and the possible solutions. The future of LEP is contained in its acronym, i.e. Luminosity, Energy and Polarization. The status of the development programmes is presented.

2 PERFORMANCE

Operational performance

	Inj.	Ramp	Coast	Fault
average	2:42	0:55	7:52	1:31
rms	2:03	0:23	5:04	2:18
best	0:30	0:12	22:35	0:00

Table 1: Statistics on the LEP runs

LEP is operated 50 % of the time at the Z^0 peak and 50 % at intermediate energies within ± 3 GeV of the peak. The integrated luminosity in 1990 (a total of 750000 Z^0) was 10 times larger than in 1989 (fig 1). During 1990, the integrated luminosity per week has been increasing steadily from 0.5 pb^{-1} to 1.4 pb^{-1}. The physics events were clean after automatic positioning of the 72 collimators. Very clean conditions were obtained by fine optimization.

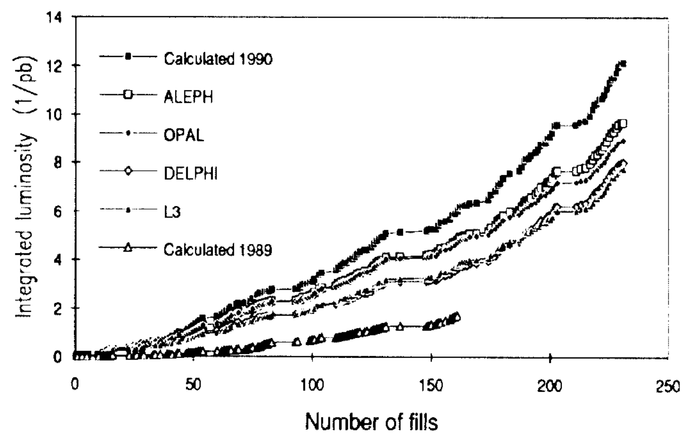

Figure 1: Integrated luminosity in 1989 and 1990

The availability of the machine was 50 % , partly due to the large number of machines in series and the size of LEP. It is actively worked up. The long set-up time (table 1) is compensated by the very long coasts [1].

Peak performance

The peak performance, often obtained during machine studies, is close to design, showing that the machine behaves basically as expected.

Parameter	Design	Achieved
Current per bunch (mA)	0.750	0.780
Current per beam (mA)	3.000	2.980
Current in both beams (mA)	6.000	4.700
V. beam beam parameter (ξ_y)	0.040	0.017
H. beam beam parameter (ξ_x)	0.040	0.035
Emittance ratio (ϵ_y/ϵ_x)	0.04	$\sim$ 0.01
Luminosity ($10^{30} cm^{-2} s^{-1}$)	16.0	$\sim$ 7.0
β function at the IP (β_v^*) cm	7.0	3.2

Table 2: Achieved (peak) and design LEP performance

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Energy calibration

An original method was developed [2] taking advantage of the availability of protons. If electrons and protons circulate on the *same* central orbit, the difference in revolution frequencies is an absolute measurement of the electron energy, to the accuracy of the knowledge of the particle masses. The central orbit can be accurately found by its insensitivity to the excitation of the sextupoles. The accuracy is ±1 MeV per beam at 20 GeV. Extrapolated at the Z^0 energy, it reaches ±20 MeV in the centre-of-mass.

3 MAGNETIC OPTICS

Description

The LEP optics is structured so as to separate its main functions: 8 arcs, 16 dispersion suppressors, 16 RF, 4 high-β and 4 low-β straight-sections. The cell phase advance in the arc is 60° and the chromaticity is corrected by six sextupole families. Since the switch-on of LEP, the optics has been modified twice. The integer parts of the betatron tunes were changed from 70/78 to 71/77 by rematching the four high-β insertions. The purpose was to avoid a very strong linear coupling resonance driven by an unexpected defect of the vacuum chamber [3]. The linear betatron coupling is now well compensated.Emittance ratios below design were observed (1%). The β_y^* in the low-β insertions was reduced from the nominal 7 cm to 5 cm for operation.

The optical model, in the MAD language, includes the nominal fields as well as the known field imperfections. Its predicts the important operational parameters (tunes, closed orbit, β^*, betatron coupling) very well. It partially fails in predicting the linear chromaticity, the parasitic dispersion and the dynamic aperture at injection.

Injection, ramp and squeeze

The LEP cycle from injection to physics consists of some 20 intermediate optics configurations. Apart from the synchronization of the insertion quadrupoles, no significant problems have been encountered in accelerating whatever current was accumulated. However the procedures are complex and time consuming. They are being improved by the introduction of new software, continuous monitoring of the tunes, tune loops, reactive feedback to maintain the coherent and incoherent tunes equal and, possibly, continuous monitoring of the chromaticity.

Observations and Developments

Vertical dispersion Surprisingly, the parasitic dispersions in LEP were 2 to 2.5 higher than expected. The search for the sources is made difficult by the resolution of the orbit measurement (100 μm), which may be limited by residual coherent oscillations and the small damping aperture (.2 % without beam loss). No strong defect was isolated. The fact that the dispersion is decreased by careful correction of the vertical orbit rather points to distributed sources. Antisymmetric orbit bumps in the insertions have been used to minimize it.

In 1991, an improvement of the beam monitor resolution is expected to yield dispersion measurements accurate to a few centimeters. Closed dispersion bumps in the RF straight-sections will be provided, using small skew quadrupoles in the lattice as well as a global correction scheme.

Chromaticity and dynamic aperture Two observations are still unexplained: the measured chromaticity disagrees by 15 % with the model, with opposite signs in the two planes; the horizontal dynamic aperture at injection is 3 times less than expected. At top energy, even after β squeezing, the latter discrepancy is reduced. In practice, the chromaticity is straightforwardly corrected, and the dynamic aperture is still enough (10 rms beam sizes). There is a suspicion that, combined with synchro-betatron resonances, it might limit the current at injection. The hunt for the missing multipoles opens in 1991.

Optics asymmetries The luminosities in the four insertions differ by up to 25 % (Figure 1). A β-beating was detected and eventually explained by a longitudinal misalignment of the superconducting coils and girders of some insertion quadrupoles, enhanced by the larger sensitivity of the very low-β optics. The alignment method, made difficult by the presence of the detectors, is being improved. The matching of the insertions has been modified to allow for asymmetric insertions.

Decrease of β^* At the Z^0 peak, some aperture is left to further squeeze β^*. Calculation of the higher-order chromatic effects [4] shows no pathological behaviour when β_y^* is reduced from the nominal 7 cm to 2.54 cm (the bunch length is 1.7 cm). Experiments have confirmed so far that 3.2 cm is possible, i.e. that non-linear phenomena do not perturb the dynamics. The machine is now routinely operated at $\beta_y^* = 5$ cm. The amplification of alignment and focusing errors may set a practical limit on the lowest β-value compatible with reliable operation.

90° lattice Stronger focusing is required to reach the beam-beam limit at higher energies (LEP Phase II). Some initial experiments were carried out to test this optics at injection energy. While injection and a good set-up were rapidly obtained, a few attempts to store high currents were not successful. The development of this high-tune lattice is being pursued with high priority.

New optics developments At injection, the low field level makes LEP sensitive to very small field imperfections. To compensate for the most significant, i.e. the skew gradient, an optics with unequal horizontal and vertical phase advances was designed. The betatron coupling is self-compensated within each arc. The integer part of the betatron tunes is optimum with respect to luminosity and polarization. Although the achromatic structure of the arc cannot be retained in both planes, the higher-order chromatic properties remain well behaved. Before this optics is shown to be viable, the 71/77 optics is modified by rematching the high-β insertions to yield the tunes 70/76.

The aim is to increase the beam-beam limit and prospects for polarization.

4 COLLECTIVE EFFECTS

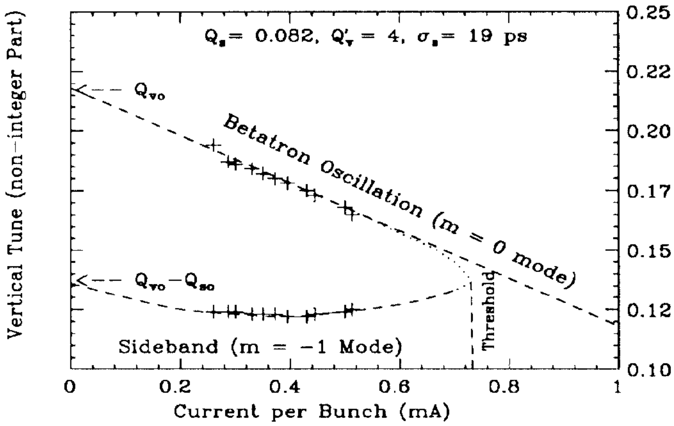

Figure 2: Observed transverse mode coupling

Transverse mode coupling instability The transverse mode coupling instability was predicted to be the most severe limitation of single bunch current in LEP. The transverse broad-band impedance of the LEP vacuum chamber was therefore minimized by very careful design. Experimental observations of the betatron frequencies of the two modes $m = 0$ and $m = -1$ (Figure 2), confirmed the impedance calculations (2.24 MΩ/m) [5]. The estimated threshold current of about 0.75 mA/bunch has been reached without instability, but at a higher Q_s (0.13).

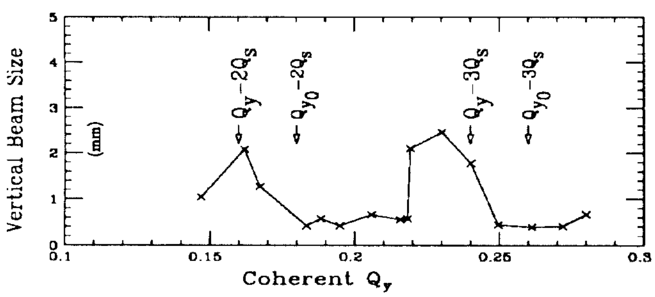

Figure 3: Synchro-betatron resonances

Synchro-betatron resonances In practice, the beam current is limited by synchro-betatron resonances. The dominant driving mechanism is the parasitic dispersion in the RF cavities. Measurements done so far indicate that the resonances are coherent (Figure 3) though incoherent ones are also present. The improvement of the optics and a betatron tune below the integer are expected to remove this limitation.

Longitudinal bunch oscillations The large spacing between bunches makes coupled bunch oscillations unlikely in LEP. However, longitudinal oscillations did indeed limit the current until a provisional longitudinal feedback was quickly installed. The absence of exponential growth and of transverse coherent oscillations, which are expected to have a relatively lower threshold, have oriented the studies towards a possible noise on the magnets or RF system. A dedicated 1 GHz feedback is under construction.

5 BEAM-BEAM EFFECT

The saturation of the beam-beam strength parameter at a value some 2.5 times lower than expected is the present major limitation (Figure 4); it causes the luminosity to

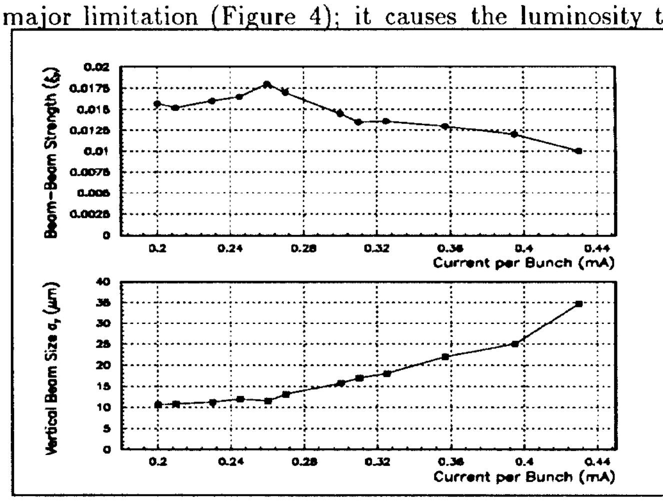

Figure 4: Beam blow-up due to the beam-beam forces

remain constant over the 5 first hours of the coasts or more.

A likely explanation, consistent with numerical simulations (fig 5) [6] and observations, is the presence of a systematic beam-beam difference resonance close to the working point ($Q_x = 71.28$, $Q_y = 77.18$):

$$2Q_x - 2Q_y = 4 \times 3$$

which reduces the luminosity by some 50 %. This harmful

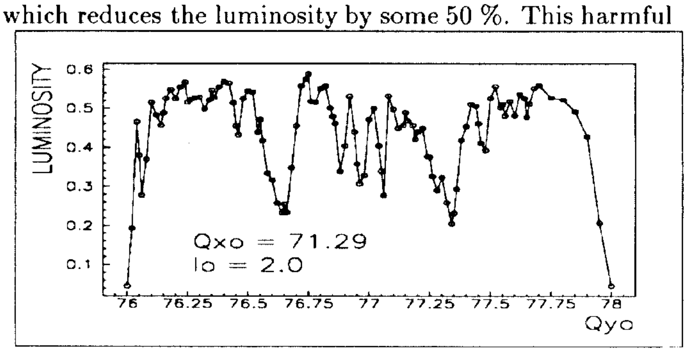

Figure 5: Simulation of the beam-beam effect

resonance will be avoided with the new 70/76 optics.

Other sources known to decrease the beam-beam limit are the optics imperfections. As already mentioned, the vertical dispersion is twice what was expected; large β-beating (20 %) and optics asymmetries (some 10 degrees in betatron phase) were identified. Numerical simulations show that improvements in the optics measurements and correction could yield a potential luminosity gain of more than 50 % . Automatic bunch equalization is as well expected to raise the beam-beam limit.

6 TRANSVERSE POLARIZATION

Transverse polarization allows the calibration of the energy to a few MeV. The capability of the LEP beams to spontaneously polarize has however been debated. The rise time of the polarization at the Z^0 peak is long (300 minutes); the depolarizing spin resonances are stronger ($\sim \gamma^2$) and denser than in other machines, to the extent that reliable predictions are difficult.

During the summer of 1990, a significant fraction of the machine study time was devoted to commissioning the Compton polarimeter, optimizing the parameters of the standard optics and refining the correction of its imperfections until a polarization degree of 10 to 20 % was predicted. After several attempts, an unambiguous asymmetry of the back-scattered photons was detected (figure 6 and [7]). The validity of the signal was assessed by internal on-line checks of the systematics and by the controlled excitation of spin resonances using a pattern of vertical orbit bumps. The polarization level, calculated in two indepen-

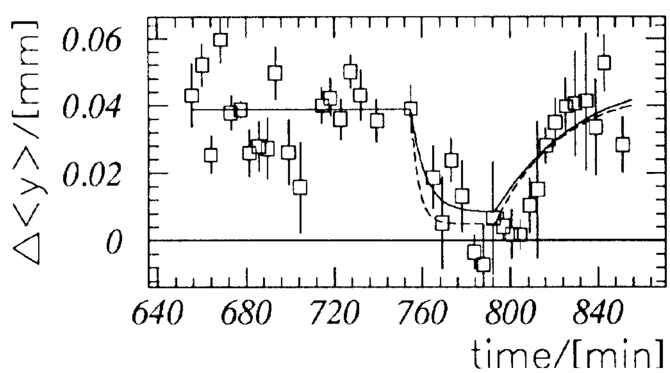

Figure 6: Observed polarization in LEP (plain line) compared to expectation (dotted line)

dent ways, was found to be 9 % ± 2% systematic ± 2 % random. In 1991, this polarization, possibly increased, will be used to calibrate the Z^0 energy and width.

7 THE ENERGY UPGRADE

Parameters of Phase II

Phase 2 of the LEP programme is approved and will take the beams up to energies beyond the W pair threshold of 82 GeV [8]. With 192 additional superconducting cavities and a target operational gradient of 6 MV/m, an energy of 92 GeV can be reached. If the effective gradient was only 5 MV/m, the energy would be reduced to 89 GeV, i.e. still significantly above the threshold. The expected luminosity, limited by the beam current (2 × 4 × 0.750 mA), is about 2 10^{31} $cm^{-2}s^{-1}$ or more. It requires the stronger focusing of 90° per cell. The luminosity may be doubled by combining the energy and luminosity upgrades.

Superconducting cavities

Two lines of development have been followed to optimize the quench behaviour of the cavities: niobium sheet metal with improved thermal conductivity and sputtering the inside surface of copper cavities with niobium. The latter approach presents a higher performance potential and has therefore be retained for the series production of 160 cavities by industry. The complement will consist of 24 Nb sheet cavities made by CERN and industry, and 8 Nb sputtered cavities made at CERN. Two 4-cavity modules of each type are presently installed in the LEP ring. The first module has been used for physics runs in 1990 already; the operational gradient was limited to 4 MV/m because of difficulties in the adjustment of the RF power coupler of one cavity. Adjustable main couplers developed in the mean-time, clean room assembly and protection from synchrotron radiation by collimators will allow to get closer to the target gradient. Four cryogenic plants with an initial cooling power of 12 kW at 4.5°K, designed to be reusable for the LHC project, will be installed in the experimental points. The installation of the new cavities is planned over 3 years and due to be completed at the beginning of 1994.

Modifications to LEP 1

The optics of all the insertions was revised or redesigned to minimize the cost of the upgrade. A better chromatic correction using 4 sextupole families was found. It provides a large dynamic aperture and small chromatic variations of the important optical parameters. Studies are presently devoted to the robustness of the dynamic aperture with respect to magnetic imperfections and asymmetrical RF acceleration.

At present four out of the 16 available RF straight sections are equipped with copper cavities. To install the full complement of 192 new cavities, klystron galleries must be dug in points 4 and 8. The underground work is being carried out with special care to prevent dust from reaching the experiments. The energy upgrade requires changing the superconducting insertion quadrupoles, rebuilding many power converters, new klystrons, new electrostatic separators and new collimators to efficiently protect the superconducting cavities and the separators. The power distribution and cooling systems for LEP will also be upgraded to handle twice the presently installed power.

8 THE LUMINOSITY UPGRADE

A pretzel scheme to collide up to 36 bunches in LEP has been shown to be attractive [9]. A low cost version of this proposal is being implemented: 8 electrostatic separators become available from the Sp$\bar{p}$S; they allow for a 8 bunch pretzel scheme, doubling the luminosity without significant modifications to other systems.

The pretzel separation is provided by four horizontal bumps, each extending over most of a quadrant of the machine (figure 7). They are antisymmetrical about the non-experimental insertions. This arrangement has the

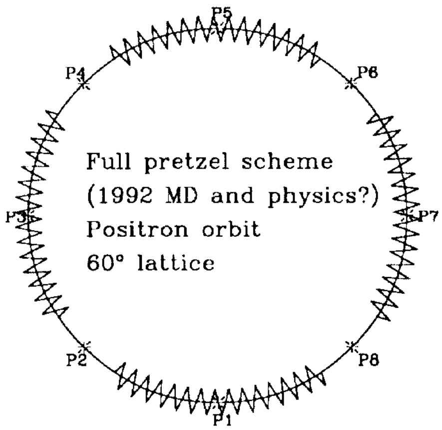

Figure 7: Pretzel separation

favourable feature of cancelling the differential optical effects. The polarity of the pretzel orbits can be chosen so that the extra separation due to the energy sawtooth effect (significant at 90 GeV) adds up. The beams are separated by 12 rms beam widths up to 90 GeV. The horizontal separation is not incompatible with polarization. The geometrical aperture of the LEP vacuum chamber and dynamic aperture around the pretzel orbits seem sufficient to ensure a good lifetime; a first experiment carried out on an orbit simulated with magnetic deflections showed no significant influence on the injection rate and maximum current.

Some copper cavities must be removed to make room for the separators, slightly reducing the maximum RF voltage. The HOM losses in the cavities and separators are calculated to be acceptable. Special care is taken to reduce the sparking rate of the separators with a low electric field (~2MV/m) and collimators to shield the electrodes from the direct synchrotron radiation. Four separators are now installed, allowing a partial pretzel scheme to be established for machine development purposes. The full complement of 8 separators will be installed in 1992 allowing further tests and, possibly, first operation with 8 bunches.

9 LONGITUDINAL POLARIZATION

To carry out precise tests of the Standard Model, the LEP physics community has made a strong case for obtaining collisions of longitudinally polarized beams in the four LEP experiments at the Z^0 energy. Meanwhile, studies have shown that the prospects for polarized beams are not as dark as often believed. The success of the transverse polarization experiment confirmed this. To run efficiently with polarized beams, the polarization degree must reach 50 % and the rise-time must be reduced. The former requires spin resonance compensation which will be tried this year. The rise-time can be reduced from 300 to 36 minutes by new asymmetrical wigglers just installed.

The polarization vector may be rotated at each crossing point by a Richter-Schwitters spin rotator. To minimize the depolarization due to the bending in the rotator, the fields have to be weak and the rotator insertion straddles many quadrupoles. The conditions for optical and spin transparency could nevertheless be fulfilled with only one additional quadrupole per half insertion. (Figure 8). A

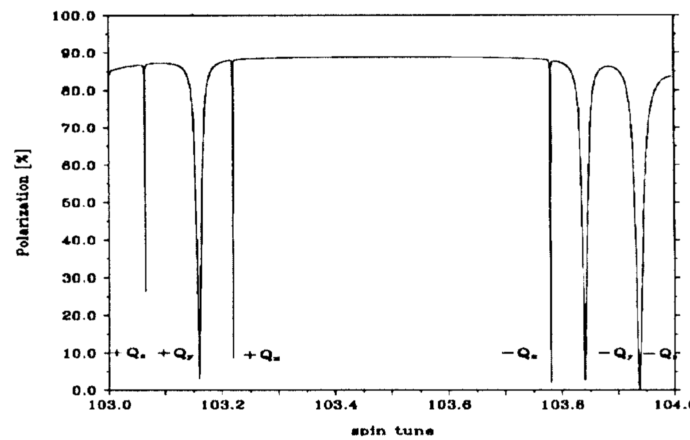

Figure 8: First-order polarization with spin rotators

collimator scheme to protect the machine and experiments from the synchrotron radiation generated by the rotator is under study with encouraging results.

Acknowledgements

The success of LEP and dynamism of its development programs is shared by the many colleagues of the Accelerator and Technical divisions of CERN.

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