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Performance Limitations at LEP

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Abstract

LEP is now used for Z^0-production in four experiments. Eight bunches per beam are injected and accumulated at 20 GeV. The beams are separated vertically in the symmetry points and horizontally in the arcs by a pretzel scheme. After acceleration the beta functions in the interaction points are reduced and the beams brought into collision. At injection the intensity per bunch is limited mainly by the transverse mode coupling instability. A large synchrotron frequency and a long bunch obtained with wigglers improve this situation. Other effects like the head-tail instability and synchro-betatron resonances impose a tight control of the chromaticities and the tunes during injection and acceleration. The limitation of the bunch intensity is slightly influenced by the interaction with the other beam. In the collision mode at 46 GeV the beam-beam effect imposes a limitation which determines presently the overall performance. It is controlled by adjusting the transverse beam emittance with wigglers in dispersive sections. A maximum luminosity of $18\ 10^{30}\,\mathrm{cm^{-2}\,s^{-1}}$ has been achieved which clearly exceeds the design value. Possible improvements using a larger number of bunches are under study. For the Z^0-physics an accurate energy calibration is important. A value of around 30 ppm has been achieved by resonant depolarization of the beam. In the future LEP will operate at about 90 GeV per beam for W-production. At this energy the beam-beam effect is weaker and methods to increase the current or to reduce the emittance are studied.

1 INTRODUCTION

The Large Electron Positron LEP operates at CERN since 1989, [1, 2]. This ring has a circumference of 26 659 m and has an approximate eightfold symmetry with 8 arcs and 8 long straight sections. The arcs contain regular FODO-cells of 79 m length and have dispersion suppressors at the ends. Four of the eight long straight sections are used for particle physics experiments with the detectors L3, ALEPH, OPAL and DELPHI. Some of these sections also contain part of the RF-system which operates with a frequency of 352 MHz.

These experiments have solenoidal fields for particle spectroscopy and are located in a low-beta section with superconducting quadrupoles being at 3.5 m distance from the interaction point. The coupling produced by the solenoid magnets is compensated with rotated quadrupoles. The nominal emittance ratio is now close to 2%. The values of the beta function in the interaction points are about 0.05 m in the vertical and 2 to 2.5 m in the horizontal plane.

The exploitation of LEP is divided into two phases: LEP I operates at about 46 GeV per beam with an originally expected luminosity of up to $14\ 10^{30}\,\mathrm{cm^{-2}s^{-1}}$ to produce Z^0-particles. This energy is obtained with about 120 Cu-cavities having a total voltage around 0.4 GV distributed over 2 long straight sections. LEP II will operate at an energy of about 90 GeV with an expected luminosity around $50\ 10^{30}\,\mathrm{cm^{-2}s^{-1}}$ to produce W^+-W^- pairs. This is made possible with the addition of 192 superconducting cavities giving a total voltage of about 2.2 GV distributed over 4 long straight sections. A total RF-power of about 30 MW will be available for the beam. With an energy loss of about 1.9 GeV per turn this will be sufficient to store a current of 8 mA per beam.

2 BASIC PARAMETERS

Apart from the beam energy the most important parameter of a colliding beam facility is the luminosity defined as the interaction rate per unit cross section. Most of the efforts described below have the goal to increase this quantity in LEP within the imposed restriction. For two beams with k bunches each having Gaussian transverse distributions with rms sizes σ_x^* and σ_y^*, number N_b of particles per bunch and revolution frequency f_0 this luminosity is

$$L = \frac{kN_b^2 f_0}{4\pi\sigma_x^*\sigma_y^*}. \qquad (1)$$

It is limited by the beam-beam effect caused by the non-linear forces between the two beams. Its linear part leads to a tune shift which is for $\sigma_y^* \ll \sigma_x^*$

$$\xi_x = \frac{N_b r_e \beta_x^*}{2\pi\gamma\sigma_x^{*2}} = \frac{N_b r_e}{2\pi\gamma E_x}, \xi_y = \xi_x \text{ if } \frac{\beta_y^*}{\beta_x^*} = \frac{E_y}{E_x} \qquad (2)$$

where r_e is the classical electron radius and β_x^*, β_y^* are the horizontal and vertical beta functions at the interaction point and E_x is the horizontal emittance.

The luminosity can be improved with the following methods: Decrease of β^*; increase of the current per bunch; if the beam-beam limit is reached one increases the emittance, otherwise one decreases it; increase of the bunch number if this is compatible with beam crossings and available RF-power. In addition the requirements for

Table 1: E_x and I_b giving $\xi = 0.03$

μ_x degrees	E GeV	E-wiggler	E_x nm rad	$I_b(\xi{=}0.03)$ mA
60	46	off	36	0.40
90	46	off	12	0.14
90	46	on	36	0.40
90	90	off	48	1.02
108	90	off	28	0.59
135	90	off	19	0.40

collimation against background in the experiments set a limitation on the maximum horizontal emittance which lies presently around 50 nm rad, [3]

The emittance of LEP can be controlled with the choice of the phase advance per cell in the arcs and with the emittance wigglers installed in a dispersive section. For the first few years LEP operated with phase advances $\mu_x = \mu_y = 60^0$. These values have been changed to $\mu_x = \mu_y = 90^0$ and later to $\mu_x = 90^0$ $\mu_y = 60^0$ both giving about the same emittance. Even higher phase advances per cell are under study for future operation at 90 GeV where the beam-beam limited current is high. The emittance wigglers have been used to increase the beam size for a given optics. They allow to vary the emittance during a run such as to adapt it to the decaying bunch current and to stay close to the beam-beam limit. This improves the integrated luminosity achieved in a run. In Table 1 the relevant parameters of the different optics modes are listed. It also gives the bunch current necessary to reach a beam-beam tune shift of ξ=0.03. This is not the limiting current since at higher intensities there is some blow-up of the bunch dimension which keeps the tune shift about constant.

The number of bunches foreseen for LEP was $k = 4$ for each beam. This is made possible by vertical separation in the four long straight sections not occupied by experiments. A horizontal pretzel scheme with electrostatic deflectors provides horizontal separation of electrons and positrons in the arcs which makes operation with more bunches possible [4]. Since end of 1992 this scheme operates successfully with eight bunches per beam. For the future a scheme is studied which increases the bunch number using relatively short bunch trains which are separated locally in the long straight section on both sides of the experiment, [5, 6, 7]. All schemes involving many bunches have to comply with a luminosity time structure acceptable by the experiments.

3 INTENSITY LIMITATION AT 20 GEV

At the injection energy of 20 GeV the current per bunch is limited by collective effects. Without any wigglers the natural bunch length is $\sigma_s \approx 3$ mm for a typical synchrotron tune of $Q_s \approx 0.085$. During accumulation this short bunch undergoes some turbulence, later longitudinal radial modes appear and the intensity is limited at about $I_b \approx 0.2$ mA by effects not well understood [8]. This limit can be improved with wiggler magnets which increase the energy spread and therefore the bunch length. Now the bunch current is clearly limited by the transverse mode coupling instability involving the modes $m = 0$ and $m = -1$. Its threshold is well described by the approximate equation [9]

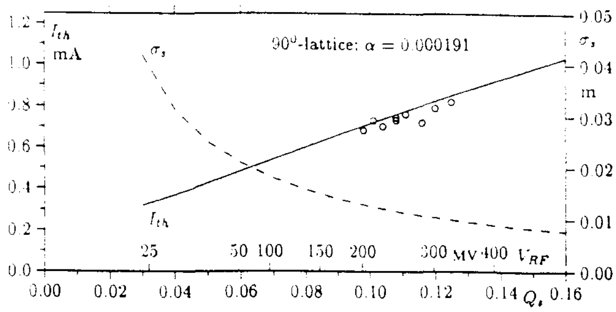

Figure 1: TMCI-thresholds and σ_s vs. Q_s

$$I_{th} = \frac{2\pi Q_s E f_0}{e\Sigma\beta k_\perp(\sigma_s)} \tag{3}$$

where Q_s is the synchrotron tune, E the operating energy, f_0 the revolution frequency, β the beta value at the location of the impedance and $k_\perp(\sigma_s)$ the transverse loss factor which depends on the bunch length. To improve the threshold we can lengthen the bunch with the wigglers to reduce $k_\perp$ or can increase Q_s to separate the two transverse modes more. Using the dependence $k_\perp(\sigma_s)$ given in [10] we find the expected threshold current shown for one beam in Fig.1 together with the measured points [11]. The maximum bunch current obtained so far is about 0.8 mA with $Q_s \approx 0.12$. However, theoretical and experimental investigations [12, 13] indicate that the current per bunch is reduced by the presence of the other beam. Wake fields induced by the electrons are seen by the positrons and vice versa. This leads to a coupled head-tail mode instability. This reduction is about 12 % for the case of four bunches per beam having vertically separated encounters in the centers of the eight straight sections and even larger for the pretzel operation which has additional encounters with horizontal separation at finite dispersion. The best current obtained in this mode of operation is 0.43 mA per bunch but with a lower synchrotron tune. This is presently more current than what can be used in collisions. All these single bunch limits can be increased in the future with a higher Q_s when more RF-voltage is available. In order to reach 1 mA per bunch we estimate that a $Q_s = 0.19$ will be necessary for two beam withs 4 bunches. Another minor gain is expected once the Cu-cavities are replaced by the superconducting ones which have a lower transverse impedance.

There are other collective effects which do not represent a basic limitation for the single bunch current but demand rather tight tolerances during operation.

The reactive part of the transverse impedance leads to a bunch current dependent coherent tune shift of about 0.13 per mA in the vertical and 0.06 per mA in the horizontal plane. This effect imposes additional restriction on the choice of tunes during injection and ramping because for some effects the incoherent as well as the coherent tune has to stay clear from resonances.

LEP also suffers from higher mode head-tail instabilities with positive chromaticity. This is probably caused by a sizable transverse impedance at very high frequencies in the shielded bellows indicated in field calculations [10]. As a consequence the chromaticity has to be kept within tight tolerances of about $0 < Q' < 1$ in both planes. This is particularly difficult during pretzel operation where field errors and beam-beam fields can make the chromaticities of the two beam slightly different. Presently attempts are made to improve this situation by stabilizing the lowest head-tail mode with the transverse feed-back system allowing for small negative chromaticities.

In the past synchro-betatron resonances represented a limitation and imposed a tight tune control at injection and also during ramping. They were mainly caused by dispersion in the cavities. Improvements in the optics and orbit correction have decreased the rms value of the residual dispersion from about 0.15 m to 0.05 m which eases this problem considerably. Also a better understanding of the synchro-betatron resonances in LEP has been obtained by detailed studies of their dependence on the bunch current and on dispersion and orbit distortions in the cavities [14]. Third and fourth order satellites of the integer resonance can be crossed with full current at 20 GeV. This is important for LEP 2 where large current with large synchrotron tunes will be accumulated and ramped.

There are a few limiting effects at injection related to beam-beam forces and pretzel operation. The vertically separated beam-beam encounters result in relatively small tune shifts. The pretzel operation with eight bunches gives an additional tune shift and spread due to the encounters in the arcs. Furthermore, the pretzel orbits lead to some optical effects like change of tune, chromaticity, beta beating and residual dispersion. This can produce slightly different tunes and chromaticities for electrons and positrons. The latter are difficult to correct and reduce the stable region for head-tail modes.

4 LIMITATIONS AT 46 GEV

After injection and accumulation the two beams are ramped to about 44 GeV. Here the beta functions in the interaction points are reduced to $\beta_x^* = 2.0\,\mathrm{m}$, (2.5 m in the previous year) and $\beta_y^* = 0.05\,\mathrm{m}$. Then the energy is further increased to the desired value chosen to scan the Z^0-resonance. This year only data at the peak of this resonance are taken and the energy is directly ramped to the final energy. The emittance wigglers are turned on to increase the horizontal beam emittance to up to 36 nm rad, the beams are brought into collision by turning the electrostatic separation off and the collimators are moved into their final positions [15] The beam-beam effect can represent now a limitation. With the ratio between the vertical and horizontal beta functions of about 0.02 the horizontal and vertical beam-beam tune shifts are the same with a limiting value of about $\xi \approx 0.03$. This is illustrated in Fig. 2 which shows the observed vertical tune shifts ξ_y as a function of bunch current [16]. This shift saturates at a current of about 0.2 mA at which the horizontal tune shift is about 0.03. For the emittance coupling of 2 % the vertical tune shift reaches about the same value but for larger coupling a lower limit is found. At the start of a run the emittance wigglers are used to increase the beam sizes to have $\xi \approx 0.03$. With decaying currents these wigglers are reduced in strength resulting in a luminosity which decays slower than the product of the bunch currents. Since the beam-beam effect itself adjusts the vertical beam size to keep the tune shift constant over a limited current range the setting of the wiggler is not critical and can be done in one or a few steps

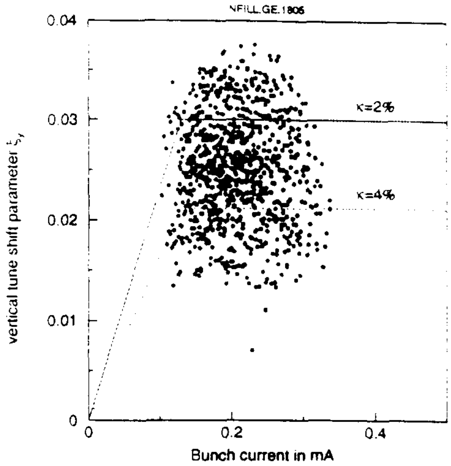

Figure 2: Vertical tune shift vs. bunch current

Some fine tuning has to be done to optimize the luminosity. Minimizing the coupling optimizes the vertical beam size and therefore the luminosity. This is done directly with the rotated quadrupoles and further optimized with the orbit correction. The latter also adjust the residual vertical dispersion which also contributes to the beam size. These two quantities can be different for orbit corrections leading to the same residual rms vertical orbit distortions but done with different strategies, e.g. different set of correctors. In one of the best runs this procedure led to average value beam-beam tune shift $\langle \xi_y \rangle = 0.034$and a peak value of $\xi_y = 0.038$[17].

The life time of the beam is not a limitation in LEP [16, 18]. It is in average 40 h and in best cases 60 h for a single or for separated beams. It is mainly determined by Compton scattering of the electrons and positrons with the black body radiation emitted by the surface of the vacuum chamber being at room temperature. For colliding beam the beam life time is typically 20 h and given by beam-beam bremsstrahlung which is proportional to the number of particles divided by the luminosity. Finding a longer life time indicates that the beams do not collide in an optimum manner and produce a lower luminosity.

The luminosity has been much improved by the increase of the bunch number from 4 to 8 with the pretzel scheme mentioned before. It uses electrostatic separators to create a closed orbit distortion in the arcs which has opposite sign for electrons and positrons. It could be possible to operate the pretzel with even more bunches.

Another scheme to increase the number of bunches uses two or four trains of 2 to 4 bunches each. They are separated on both sides of the interaction points. One version [5, 6] uses horizontal separation with a small crossing angle. One of the problems is the background due to the synchrotron radiation emitted by the beam going off center through the low beta quadrupole. This is avoided by another version [7] having head-on collisions and vertical separation starting at some distance. Early experiments have already accumulated such trains for studies with promising results.

5 LIMITATIONS AT 90 GEV

At the high energy the emittance of the beam is larger for a given optics. This, together with the higher γ, reduces the beam-beam tune shift. To gain in luminosity the current per bunch could be increased in excess of 1 mA which is difficult as mentioned before. The number of bunches can be increased using the pretzel or the bunch train scheme. The RF-power available in the cavities will limit the total current per beam to about 8 mA. If the total or the single bunch current cannot be increased sufficiently some luminosity could be gained back by reducing the emittance of the beam. To achieve this two high tune lattices are presently under study with the emittances listed in Table 1. Some beam has already been stored for these two versions. Due to the higher focusing of this optics the bunches are shorter which will lower the current per bunch slightly [11]. Taking this into account it looks at present promising to use such a high tune lattice together with a bunch train scheme to achieve a luminosity of about $70\ 10^{30}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$; [19].

6 ENERGY CALIBRATION

An important part of the physics done with LEP is the measurement of the mass and width of the Z^0-particle. This demands a high integrated luminosity to minimize the statistical error in finding the shape of this resonance and a very accurate absolute energy calibration of LEP. The energy of the beam can be determined with resonant depolarization with a relative accuracy better than 10^{-5} [20]. However, this measurement takes some time and cannot be done during a physics run. It is therefore necessary to keep track of all possible energy changes during the time interval of about 10 days between calibrations by polarization.

There are two types of effects causing an energy change. Any variation of the field in the dipole magnets results in a proportional change of the beam energy. Powered in series with these dipoles is a reference magnet with field measurement by a flip-coil and an NMR probe. Since LEP is very large not all magnets are in the same environment as the reference dipole and might age differently. About every two weeks a cross calibration is done by cycling all magnets and measuring the induced voltage in a "flux loop" lying on the pole pieces. Of course the magnet current is always measured with high precision. Finally, the temperature of the dipoles is measured with distributed thermometers to an accuracy of about $0.1\ ^0\mathrm{C}$ which corresponds to a relative energy change of 10^{-5}. In spite of all these different diagnostics systems there are some times sudden small changes observed which are not well understood.

The length of the beam orbit is an integer multiple of the RF-wave length and known with a relative accuracy of a few times 10^{-10} from the frequency measurement. However, if the magnets move the circumference of the LEP proper, defined as the orbit going through the center of the quadrupoles, can change. The beam will no longer go through these centers and get some extra deflection in the quadrupoles which will change its energy. The relation between the circumference and energy change

$$\frac{\Delta E}{E} = \frac{1}{\alpha}\frac{\Delta C}{C} \qquad (4)$$

involves the momentum compaction α. Since this quantity is very small in LEP, $\approx 2\,10^{-4}$, any relative circumference chang larger than $5\ 10^{-8}$ occurring between calibrations by polarization have to be accounted for. They can be observed by measuring the tunes as a function of RF-frequency for different sextupole strengths (like a chromaticity measurement). The frequency for which the tunes are independent of the sextupole strength corresponds to the orbit which goes through the centers of the sextupoles and, due to the close mounting, also through the quadrupole centers. In other words, the beam is on the central orbit which defines the machine circumference. Another method to observe circumference changes uses the beam orbit measuring system which has now a very high resolution [21]. It also has the advantage that this can be done at any time without disturbing the machine operation. The largest short term changes of the circumference are due to the earth tides induced by the moon and the sun [22]. Since this effect is very regular it can easily be accounted for. However, there are other changes observed which are not too well understood and seem to be related to periods of rain, atmospheric pressure changes, etc. and limit the accuracy of the energy determination.

Using careful analysis of the small unexpected changes in field and circumference and applying all the mentioned corrections an accuracy of about $3\ 10^{-5}$ for the relative energy has been achieved in 1993 which is close to the desired value of $2\ 10^{-5}$.

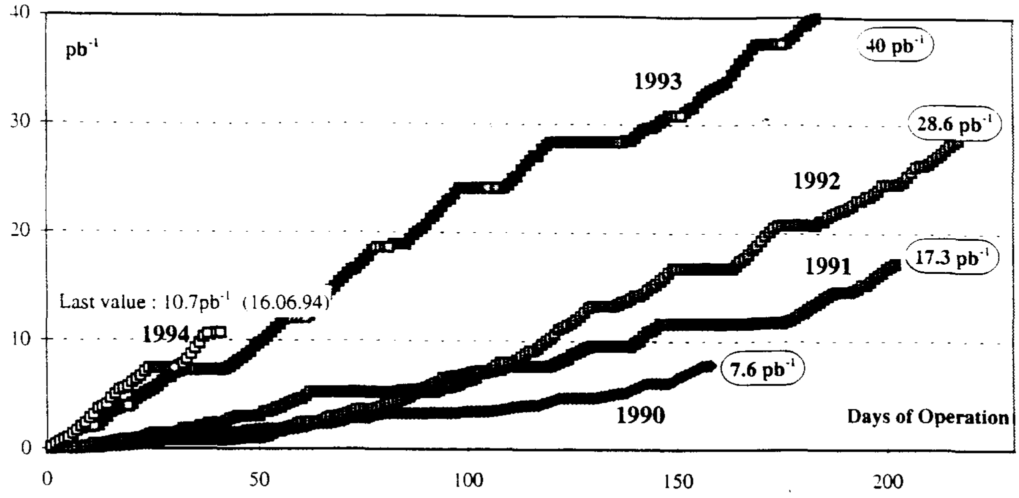

Figure 3: Integrated luminosity for the last few years

7 SUMMARY

At injection the current per bunch is presently limited by transverse mode coupling. This can be improved by increasing the synchrotron tune and by lengthening the bunch with wigglers. The presence of another beam makes this effect slightly worse due to some coupling via the wall impedance. During collisions at 46 GeV the beam-beam effect imposes a luminosity limit. Increasing the beam sizes with the emittance wigglers improves the beam currents which can be collided and gives better initial and average luminosity. Increasing the number of bunches using a pretzel scheme or bunch train with separation also increases the luminosity. At 90 GeV the beam-beam effect is weaker and larger bunch current could be used in collision. Strong focusing lattices can reduce the emittance and improve the luminosity. The accuracy of the LEP energy measurement represents a limitation for the determination of the energy and width of the Z^0-resonance. Calibration with resonant depolarization is very accurate but can presently only be done at long intervals. Changes of the dipole field and the LEP circumference have to be accounted for. Presently small changes of these parameters caused by effects not well under control give the strongest limitation to the accuracy. Frequent calibration involving polarization are the most effective way to improve the situation.

The best parameters achieved so far are [23]:

I_b one beam, 20 GeV	0.82	mA
I_b in collision, 4 × 4 bunches	0.45	mA
I_b in collision, 8 × 8 bunches	0.35	mA
ξ for 4 × 4 bunches	0.042	
ξ for 8 × 8 bunches	0.04	
L for 4 × 4 bunches	12	$10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
L for 8 × 8 bunches	18	$10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Probably the most important parameter indicating the overall performance is the integrated luminosity in a given year. The development if this quantity is shown in Fig. 3. The horizontal parts of these curves, indicating vanishing luminosity are mostly due to time spent for maintenance, installations and machine developments and to a smaller part due to failures.

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