LEP IMPERFECTION DIAGNOSIS AND CORRECTION

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This paper describes the LEP commissioning experience gained up to now on imperfection diagnosis and possible corrections. It summarizes the work done and the results collected by a number of people on beam optics, collective effects and beam-beam interactions. Concerning optics imperfections, the questions of the strong betatron coupling observed, its possible sources and ways to reduce the consequent undesirable effects are emphasized. Other observations on dispersion, optics irregularities, chromaticity and dynamic aperture are briefly mentioned. Under collective effects, predictions and measurements of transverse impedances and mode-coupling instability threshold are presented, together with results on the longitudinal impedance and the unpredicted coupled-bunch oscillations, damped by feedback. Recent measurements of synchro-betatron resonance effects observed in varying bunch current and vertical tune are also reported. For beam-beam interactions, the experimental limit on the beam-beam strength parameter and its dependence on the tunes are shortly discussed. The concluding remarks underline that the understanding of these imperfections and their correction make it possible a continual improvement of the LEP performance.

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LEP Imperfection Diagnosis and Correction

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Abstract

This paper describes the LEP commissioning experience gained up to now on imperfection diagnosis and possible corrections. It summarizes the work done and the results collected by a number of people on beam optics, collective effects and beam-beam interactions. Concerning optics imperfections, the questions of the strong betatron coupling observed, its possible sources and ways to reduce the consequent undesirable effects are emphasized. Other observations on dispersion, optics irregularities, chromaticity and dynamic aperture are briefly mentioned. Under collective effects, predictions and measurements of transverse impedances and mode-coupling instability threshold are presented, together with results on the longitudinal impedance and the unpredicted coupled-bunch oscillations, damped by feedback. Recent measurements of synchro-betatron resonance effects observed in varying bunch current and vertical tune are also reported. For beam-beam interactions, the experimental limit on the beam-beam strength parameter and its dependence on the tunes are shortly discussed. The concluding remarks underline that the understanding of these imperfections and their correction make it possible a continual improvement of the LEP performance.

1.0 Introduction

Since this was the subject of an invited talk in the 5th ICFA Beam Dynamics Workshop on "Effect of Errors in Accelerators", the selected topics concern the LEP imperfections that have been observed and were candidates to performance and intensity limitations. The most important ones are the betatron coupling related to the particular construction of the vacuum chamber (section 2), the transverse and longitudinal instabilities linked to the impedance of bellows and cavities (section 3), the synchro-betatron resonances associated with spurious vertical dispersion (section 3) and the beam-beam interactions depending on optics quality and choice of tunes (section 4). Corrections and remedies chosen are described in each case, and measurement illustrations are given whenever they are relevant.

2.0 Optics Imperfections

2.1 *Betatron Coupling*

An abnormally large betatron coupling was soon discovered during early LEP commissioning. It manifested itself by coupling the first-turn trajectories, tilting and blowing-up the beam on synchrotron light monitors and confusing the measurements of the tunes and the control of the ring.

2.1.1 Observation measurements. Vertical injected trajectory induced by horizontal kicks at various azimuths¹ pointed out that the coupling sources were distributed in all the arcs but did not occur in the straight-sections. Vertical orbit deviations excited by horizontal bumps closing after one full oscillation or over one arc indicated that the average parasitic skew-gradient was about 2 Gm^{-1} , of similar amplitude in all arcs except arc 4 where it was smaller. This imperfection did not scale with beam energy and studying the difference and sum responses to positive and negative bumps showed that it is mainly a linear component (skew-quadrupole) with only a weak skew-sextupole (mainly in arc 4).

Vertical dispersion is expected from strong coupling in regions with finite horizontal dispersion and was measured to be 20 to 40 cm. Such a dispersion contributes of course to the vertical emittance. However, the results obtained for coupling, dispersion and emittance are not completely consistent.

Excitation of linear resonances could be observed. Sum resonances provoke beam growth according to

$$\epsilon_x - \epsilon_y = \text{constant, for } Q_x + Q_y = p \quad (1)$$

where ϵ and Q are emittances and tunes, respectively. Difference resonances induce beam transverse-beating or amplitude-exchange following

$$\epsilon_x + \epsilon_y = \text{constant, for } Q_x - Q_y = p \quad (2)$$

These two resonances are characterized by their driving terms, also called coupling coefficients²,

$$C^\pm = \frac{1}{4\pi} \oint \sqrt{\beta_x \beta_y} \left[2K + M \left(\frac{\alpha_x}{\beta_x} - \frac{\alpha_y}{\beta_y} \right) - iM \left(\frac{1}{\beta_x} \mp \frac{1}{\beta_y} \right) \right] \times \exp \left[i \left(\mu_x \pm \mu_y - \Delta^\pm \frac{s}{R} \right) \right] ds \quad (3)$$

with $\Delta^\pm = Q_x \pm Q_y - p$, i.e. the distance from resonance. K is the normalized gradient of the skew-quadrupole and M is proportional to a solenoid longitudinal-field. Measuring $|C^\pm|$ on the nominal optics (tune integers separated by 8) gave an estimate between 0.2 and 0.5 at 20 GeV/c, i.e. much larger than expected.

2.1.2 Possible sources. Among the expected sources of linear coupling, there are three that have been considered as important and estimated in the design phase³. Indeed the random tilts of all quadrupoles of r.m.s. value $\langle \Theta \rangle$ and finite amplitudes of the vertical orbit (r.m.s. $\langle y \rangle$) in the systematic sextupoles required for chromaticity correction generate coupling, estimated to be

$$\begin{aligned} |C^\pm| &\equiv 0.009, \quad \text{for } \langle \Theta \rangle = 0.24 \text{ mrad} \\ |C^\pm| &\equiv 0.012, \quad \text{for } \langle y \rangle = 1.0 \text{ mm} \end{aligned} \quad (4)$$

on the nominal optics. The third source was of course the experimental solenoids, of which the strongest field integral corresponds to $|C^\pm| \equiv 0.06$. This result justified the introduction of tilted quadrupoles near each interaction point (total of 8) to reduce every solenoid contribution⁴ to below ~ 0.003 .

There remain however sources due to field imperfections, initially considered as negligible, like field asymmetries in the magnets, earth field, induced current in a dissymmetric vacuum chamber

and presence of magnetic material perturbing the field lines. One of those has to be responsible for the observed $|C^*|$ that is an order of magnitude too high. Measurements rule out the earth field as main contributor and the consequent skew-gradient estimated by including the shielding effect of the dipole is only about 0.15 Gm^{-1} . The importance of asymmetries has not been precisely quantified, but the presence of ferromagnetic Nickel in the contact layer between the Aluminium chamber and the lead coat was identified as the main source of unexpected perturbations⁵. The Ni-layer (electrolytic deposition) is about $7 \mu\text{m}$ thick ($\sim 1 \text{ ton}$ in LEP), which gives an approximately infinite ratio length over thickness. Hence, the remanent field is not changed by the vertical dipole field in horizontal faces of the chamber, but only in inclined faces. Furthermore the remanent field B_r can be strong, since Nickel has a high H_c ($\sim 60 \text{ Oe}$) and rectangular hysteresis cycles (saturation field of 0.61 T). The actual origin of high B_r in LEP is not known, but probably related to some mechanical or construction process. In any case, B_r of the horizontal faces creates the undesirable skew-field (Fig. 1).

Fig. 1 Calculated field map, given by the Ni-layer

Suppressing B_r in the vacuum chamber Nickel layer implies demagnetization with an alternate tangent field. Solenoids and C-shape magnets with horizontal field, both surrounding the vacuum chamber, can be used and in-situ demagnetization without chamber removal (with a simple coil slipped between the chamber and the magnet yoke) is possible.

In February 1990, and during 90-91 shutdown, 5 sections have been demagnetized with solenoids and C-magnets. It is foreseen to demagnetize the whole ring in-situ during 1992 shutdown. In the mean time and during past commissioning, corrections are and were required using tilted quadrupoles and optics optimization.

2.1.3 Initial coupling compensation. It was first appropriate to re-optimize the linear optics of LEP in order to modify the tune-integer separation, for the collider was difficult to control and the source of imperfections had the periodicity 8 of the arcs. With tune integers separated

by 6 ($Q_x = 71.4$, $Q_y = 77.3$), the driving term amplitude (3) of the difference resonance was reduced by 5 approximately, but still large

$$|C^-| = 0.058, \text{ for } (Q_x - Q_y) = 6 \quad (5)$$

The next step consisted in trying to compensate linear coupling⁶ by using the tilted quadrupoles already installed near each of the 4 experimental area. For the necessary solenoid compensation, there are four pairs (or families) around every even crossing point able to entirely decouple betatron motions outside the experimental sections and at the interaction position. The corresponding pairs of magnets are termed QT1 to QT4, the elements of a pair being symmetrically placed with respect to the solenoid center. Antisymmetrically powered, these elements generate an imaginary component C^- , while they create a real component when powered with the same sign. The two pairs QT2 and QT3 are antisymmetrically powered to mainly compensate for the solenoids (imaginary C^- , usually) while the magnets of QT1 and QT4 are independent in order to give means of compensating ring imperfections. Their strengths were estimated such as to give a margin of about 2 at maximum energy (~ 100 GeV) with respect to expected imperfections, hence of ~ 10 at injection. This made it possible to use them for correcting the strong systematic coupling due to the vacuum chamber. Note also that the 4×4 families of tilted quadrupoles were introduced from the beginning so that both C^- and C^+ be simultaneously compensated, i.e. second order tune shifts and first order β -beating be taken care of.

Since the working point is close to a difference resonance, the efforts for correcting the ring imperfections were focused on the reduction of C^- . Measurements concerned mainly the normal mode frequencies obtained from horizontal and vertical pick-ups

$$Q_{n.m.} = Q \pm \frac{1}{2} \sqrt{\Delta^2 + |C^-|^2} \quad (6)$$

which are closed to the tunes when Δ is much larger than $|C^-|$, but exactly separated by $|C^-|$ when Δ vanishes. Observation of the luminescent screens could give a qualitative idea of the beam aspect ratio that also depends on the coupling strength,

$$\frac{\epsilon_y}{\epsilon_x} = \frac{|C^-|^2}{|C^-|^2 + 2\Delta^2} \quad (7)$$

The first successful compensation was obtained by the author using the optics with $(Q_x - Q_y) = 6$ and the QT1 tilted quadrupoles⁶. It was based on the observation supported by numerical simulations that a second harmonic of skew-gradient correction had strong effects on coupling with this optics, for the source of the imperfections was mainly an harmonic 8. Subsidiarily, two arcs enclosing one crossing point and having approximately symmetrical errors generate a real component C^+ at this point. Both arguments incited us to excite the QT1 according to the following pattern (e.g. L2 = left of point 2 and R2 = right of point 2),

Position	L2	R2	L4	R4	L6	R6	L8	R8
QT1 Polarity	-	-	+	+	-	-	+	+

and with a QT1 absolute normalized strength of 0.002 m^{-2} at 20 GeV.

The first "historical" compensation succeeded to decrease $|C^-|$ by more than an order of magnitude, down to 0.001, as shown in Fig. 2. The corresponding change in the beam aspect ratio, at positions with and without horizontal dispersion (top and bottom), can be seen in Fig. 3. This correction made the control of the machine much easier and physics runs successful.

2.1.4 Further developments of compensation schemes. In an attempt to distribute the compensation in the arcs and to include the possibility of some vertical-dispersion (D_y) control, one pair of small tilted quadrupoles was added near the center of each arc. The two magnets are separated by 9 cells (or 3π for a phase of 60° per cell) so that they generate finite C^- and closed D_y -bump when they have same sign, but no C^- and D_y oscillations around the ring when they are opposite. The integrated strength of these 16 elements is of 1600 Gauss. In addition, two pairs of similar tilted quadrupoles were also installed in the dispersion suppressors (arc ends) enclosing the two straight sections (in points 2 and 6) that contain RF-cavities. In this way, D_y can be controlled in the accelerating structures (bumps closed after 4 or 5 oscillations) with the hope of acting on the synchro-betatron resonances, that might be a source of limitation (section 3).

More recently, a proposal⁷ made during LEP commissioning has been explored. Since the vertical dispersion is not entirely due to parasitic skew-gradients and the dynamic aperture (depending on the chromaticity correction quality) is not critical, it looks attractive to try a modification of the phase advances per cell in order to minimize or cancel C^- within one single arc. In this way, coupling compensation would not constrain the integer tunes anymore, which could be selected to favour polarization build-up and create good conditions with respect to beam-beam effects (section 4). Developing K in azimuthal harmonics, the ring integral (3) can be split in arc integrals which combine as follows⁸

$$C^- = \frac{1}{2\pi} \sqrt{\beta_x \beta_y} \sum_{n=-\infty}^{+\infty} K_n \int_{\text{arc}} \exp \left[\left(\mu_x - \mu_y - \Delta^- \frac{s}{R} - n \frac{s}{R} \right) i \right] \sum_{k=0}^7 \exp \left(i \frac{\pi}{4} (p-n)k \right) (8)$$

For LEP that has 31 cells per arc, the special choice $\mu_x = 71.5^\circ$ and $\mu_y = 60^\circ$ implies that the phase difference $\mu_x - \mu_y$ wanders from 0° to 360° along one arc. Hence, the vectors of the dominant contribution K_0 are regularly distributed around the origin and add to zero for small Δ^- . Therefore, there is no constraint on $p = \{Q_x - Q_y\}$ and free choice of the tune integers, that are adjustable in the long straight sections. Under these conditions, the residual $|C^-|$ should be around 0.006 (measured 0.008), but D_y not necessarily minimized anymore (measured r.m.s. value of ~ 30 cm).

2.2 Other optics imperfections

2.2.1 Vertical dispersion. The vertical dispersion measured after good orbit correction ($\lesssim 1$ mm r.m.s.) is about 20 to 25 cm on the optics with 60° per cell in both planes. The resolution of the measurements is limited by the accuracy of the orbit monitoring (100 μm) and by the small damping aperture (2 % without beam loss). However, results⁹ indicate that D_y is 2 to 2.5 larger than expected and the imperfection sources are distributed. Note that the phase advance of exactly 60° is the best tool to minimize the contribution to D_y of the systematic coupling for there is cancellation over 6 cells. Corrections have been applied using either anti-symmetric bumps in the insertions or the additional tilted quadrupoles mentioned in section 2.1.4.

Fig. 2 Tune separation on the resonance, with and without QT1 compensation

Fig. 3 Beam aspect at the light monitors, with and without compensation

2.2.2 Optics irregularities. Variation of luminosity in the four insertions reaching 25 % were observed. They were related to phase errors and betatron-beating was detected. This was first associated with a longitudinal misalignment of superconducting quadrupoles of some insertions and the matching of the insertions was modified to allow for asymmetries. More recently, the uncertainty on the energy calibration was also suspected to induce β -beating. Since the LEP dipoles filled with concrete are subject to ageing, the energy for a given excitation current decreases with time (of the order of 1 %/oo since start-up) but the quadrupole settings remain based on the field measured in the steel-only reference magnet. The resulting discrepancy produces a significant mismatch of the optics and β -beating. Updating accordingly the field calibration table compensates a large part of the observe effects.

2.2.3 Chromaticity and dynamic aperture. The measured chromaticity with a 60° / cell lattice differs from expected by 15 % with opposite signs in the two planes. The horizontal dynamic aperture, that depends in particular on the chromaticity correction scheme, is about 3 times smaller than predicted at injection, while this discrepancy is reduced at 45 GeV. The chromaticity can of course be easily corrected and the dynamic aperture still exceed 10 r.m.s. beam size ($\sigma_x \approx 2.0$ to 2.5 mm). That effect however, combined with synchro-betatron resonances (section 3), might limit the current at injection and suggests that there are still unknown multipoles present in the ring. It is interesting to note that with a 90° / cell lattice, the onset of head-tail instability depends not only on the chromaticity control, but also on the wiggler configuration (bunch-length and energy-spread increase) and the RF frequency setting around the nominal value¹⁰. This suggests a nonlinear behaviour of the tunes with $\Delta p/p$, i.e. a substantial deviation from a constant chromaticity.

3.0 Collective effects

3.1 Transverse impedance and instability

The transverse mode coupling instability has been predicted to be the most severe limit on the single bunch current. For the short LEP bunches (~ 18 mm), it was expected to manifest itself as a coupling between the vertical betatron oscillation (mode $m = 0$) and the first lower synchrotron side band (mode $m = -1$). The RF circular cavities contribute equally in the two planes, and represent the dominant part of the transverse impedance in LEP ($\sim 2,24$ M Ω /m). However, since the vacuum chamber height in the arcs is slightly above half its width and the transverse impedance varies with the second to third power of the radius, the effect of the bellows are expected to be rather strong in the vertical plane. Consequently, much effort was spent on shielding the bellows (~ 3000) and minimizing the broad-band impedance of the vacuum chamber.

Transverse impedances have been calculated from measurements¹¹ of betatron tune shifts with current, by virtue of

$$\frac{dQ}{dI} = \frac{\text{Re}}{2\pi\sigma_z E} \sum_i \langle \beta \rangle_i Z_{Ti}^{\text{eff}} \quad (9)$$

where $\langle \beta \rangle_i$ is the average beta function at the transverse impedance Z_{Ti} . The effective transverse impedance is proportional to the real one with a factor that depends on the broad band resonant frequency and tends to 1 if this frequency is high. The estimated resonant frequencies of the cavities and bellows are about 2 and 8 GHz, respectively. Adding the fact that the average beta at cavities is about half the value at bellows, both elements contribute almost equally to the tune shifts at injection. Measuring the frequency shifts per mA at 20 GeV gave for the actual impedances

$$Z_T^{\text{cav}} = 2.0 \pm 0.7 \text{ M}\Omega / \text{m}$$

$$Z_T^{\text{bel}} = 0.18 \pm 0.06 \text{ M}\Omega / \text{m}$$
(10)

in relative agreement with expectation (factor two for Z_T^{bel}).

An estimate of the single bunch threshold current was obtained from tune measurements of the two modes involved, as functions of bunch current¹². The bunch length was increased (2 to 3 cm) by exciting the wiggler magnets (1T) and the current varied between $\sim 200 \mu\text{A}$ and $515 \mu\text{A}$. With these parameters and a positive chromaticity of 4 to 10, the first satellite could be observed. Fig. 4 shows the measured data with a surprisingly large negative slope of the satellite tune. The shielded bellows impedance that has a much higher resonant frequency ($> 8 \text{ GHz}$) than the cavities, is inductive below this value and gives a negative contribution to the slope of $m = -1$ mode. However, its value is too small to explain the observation. Extrapolation of the two modes, which attract each other at higher currents due to the real part of the impedances, yields a threshold around 0.75 mA / bunch (Fig. 4), i.e. the design value. Nevertheless, this threshold cannot be reached with nominal Q_s (0.082), but with a higher value like 0.13 (and bunches 2-3 cm long), perhaps in connection with synchro-betatron resonance effects.

Fig. 4 Measurements of transverse modes, versus the bunch current

3.2 Longitudinal phenomena

Significant bunch lengthening has been observed for current above $\sim 100 \mu\text{A}$ / bunch, as expected at injection energy in relation with turbulent instability. The measurement of the corresponding threshold^{11,12} allows an estimate of the longitudinal impedance, using the stability criterion for bunched beams,

$$\left| \frac{Z}{n} \right|_{\text{eff}} = \frac{FhV_{\text{RF}} \cos \phi_s}{\sqrt{2\pi} I_{\text{thr}}} \left(\frac{\sigma_z}{R} \right)^3 \quad (11)$$

where the form factor is close to one (1.4 for resistive impedances). Eq. (11) gives the "effective impedance", weighed over the bunch frequency spectrum and acting on very short bunches. As in the transverse case, it is proportional to the usually quoted low frequency impedance, with a factor that depends on the resonator frequency and tends to 1 for long bunches. For the broad band resonant frequency of the RF cavities (main contributors) of $\sim 2 \text{ GHz}$ and a bunch length of about 18 ps, this factor amounts to 0.09 and the usual quantity termed impedance becomes

$$\left| \frac{Z}{n} \right|_{\text{low Freq.}} = 0.25 \Omega \quad (12)$$

somewhat lower than the predicted value (0.9Ω). Part of the difference comes perhaps from the selection of the form factor and resonator frequency.

Fig. 5 shows the measured "full-width" bunch length versus current, using the data from a pick-up button. Since the physical size of the button corresponds to 107 ps and is large with respect to the bunch length below turbulent threshold (full width of $\sim 30 \text{ ps}$), a correction must be applied to raw data. Approximating the pick-up response with a gaussian, the correction is a quadratic subtraction, the amplitude of which is given by the extrapolated bunch length at infinite voltage ($\sim 30 \text{ ps}$). Bunch shortening below threshold indicates a capacitive impedance for very short bunches and the estimated threshold is at $85 \mu\text{A}$ for a bunch of 15.3 ps r.m.s. The use of a streak camera avoids corrections and confirms these measurements.

Coupled bunch oscillations, made improbable by the large spacing between bunches, have been observed and did indeed limit the current in the absence of feedback. The frequency spectrum of these occasional oscillations showed synchrotron sidebands on all revolution harmonics in addition to the multiples of the bunch frequency. This indicates that modes $n = 1, 2, 3$, shifted in phase by $n \cdot \pi/2$ were present, even if the mode $n = 0$, where all bunches oscillate in phase, was the strongest. Such a behaviour might be expected if some RF cavities were tuned to a higher frequency. The irregular appearance of these longitudinal oscillations at high RF voltages also, is likeley due to the large number of higher modes in the 128 5-cell cavities. The frequencies of these modes vary with temperature, pressure and tuner positions and their accidental overlap with the coupled-bunch mode frequencies may induce instabilities. The resulting limitation has been removed by a provisional 352 MHz feedback system¹³, which dumps dipole oscillations. The phase between bunch and the RF frequency is measured, processed and used to modulate the drive signal of the RF-unit klystrons. A 1 GHz dedicated feedback system is planed. Fig. 6 shows longitudinal instabilities observed on a mountain range display¹⁴ taking the signal of a wideband pick-up.

Fig. 5 Measurements of the bunch length, versus the bunch current

Fig. 6 Observed signal (2 revolutions/trace, 500 ps/division) of a quiet (left) and oscillating (right) beam

3.3 Synchro-Betatron-Resonances

Systematic investigations of synchro-betatron resonances¹⁵ (SBR) was recently carried to study their possible role in intensity limitation, in relation with the spurious dispersion observed and dispersion bumps generated in the RF cavities. With tune integers equal to 70/76 and $Q_s \approx 0.086$, two different scans were performed. Firstly, the coherent tunes were measured as functions of beam current,

by scraping the beam, initially at 612 μA . The incoherent tunes stay constant while the coherent ones increase, crossing therefore resonance satellites, as the current decreases. For instance, vertical bunch instability was observed when the vertical coherent tunes were slightly below the resonance $Q_y = 3 Q_s$. Secondly, the vertical emittance was measured as a function of Q_y , at constant Q_x and for a beam current of $\sim 200 \mu\text{A}$. It shows sharp peaks at Q_y -values just below $3Q_s$ and $2Q_s$ (Fig. 7). As the incoherent vertical tunes are far away (~ 0.023) from SBR, these observed resonances have to be coherent. An interesting fact is that the lifetime shows dips corresponding to the emittance peaks (shifted towards lower Q_s values, may be because of the tune spread in the bunch). If this correlation is true, it is a possible mechanism limiting the intensity in LEP; for higher currents, the split between coherent and incoherent tunes increases and the tune diagram-region free from SBR is reduced. For Q_y close to 0.2, a vertical beam pulsation at intervals of a few seconds was noticeable, and this phenomenon could perhaps be explained by the coupling resonance $Q_x - Q_y = Q_s$. Note that if Q_s was in fact slightly below 0.086, the observations would better agree with the resonance line positions. It is also remarkable that not all instabilities watched during this investigation could be explained by SBR's.

The remedy for this instability mechanism is a careful choice of the tunes (beside a "good" control of the dispersion). A suggestion was to use working points with Q_y above an half-integer, as in these conditions numerical simulations predict higher thresholds for SBR's and better performance was achieved in TRISTAN. A short attempt¹⁶ was made with decimal parts of Q_x and Q_y near to .73 and .62, but the maximum current was limited to lower values than on the usual working point. However, TRISTAN experience indicates that a good tune optimization may take weeks and the spectra of vertical feedback pickups changed significantly. They were more quieter (lower resonance excitation) and practically only the synchrotron frequency was visible.

4.0 Beam-beam effects

As discussed in Section 2.1.3, the presence of strong linear coupling compelled a modification of the tunes. During the year 1990, the working point was therefore around 71.3 / 77.2. In the design conditions, the tune values were chosen near 70 / 78 in order to optimize the luminosity and the beam-beam strength parameter ξ was estimated to be 0.06 at 45 GeV, with 3 mA per beam and separated beams in crossing regions. When the beams collide, possible blow-up must be taken into account and the consequent reduction of ξ was deduced from numerical simulations and phenomenology (asymptotic value of 0.04). By comparison, the maximum observed value with the 1990 optics mentioned was around 0.015 to 0.018, i.e. a value some 2 to 2.5 lower than expected (Fig. 8). This saturation of the beam-beam strength was a major limitation and caused the luminosity to remain constant over more than 6 to 8 hours at the beginning of physics runs, albeit the beam intensity decreases.

There is an explanation of this limitation, which is consistent with observations and numerical simulations. Beam-beam effect and luminosity were indeed computed¹⁷ for initial vertical tunes between 76 and 79, constant horizontal tune of 71.29 and beam current of 2 mA (Fig. 9). Results of this scan show the presence of two systematic beam-beam resonances in the neighbourhood of the 1990 working point,

$$\begin{aligned} 3Q_y &= 232 \\ 2Q_x - 2Q_y &= 12 \end{aligned} \tag{13}$$

which manifest themselves by a dip (up to a factor 2) in the luminosity. This explains why it was better to run with Q_y near 77.2 rather than 77.3 as quoted in section 2.1.3. More effective is to change the tunes, keeping the difference equal to 6, to move them in a region free of strong beam-beam

Fig. 7 Synchro-betatron resonance lines in the tune diagram and observed vertical emittance growth

Fig. 8 Measured beam-beam strength saturation and vertical blow-up, versus current

Fig. 9 Simulated relative luminosity versus Q_y . (A = Design value, B = 1990 value, C = 1991 value)

resonances and promising a higher luminosity (hope for a gain of the order of 50 %). The corresponding new working point (Fig. 9), used during the year 1991 (see for instance in section 3.3) was therefore,

$$Q_x = 70.26, \quad Q_y = 76.20 \quad (14)$$

and this was giving simultaneously good conditions for coupling compensation and beam-beam interactions.

Another intrinsic possibility to increase the beam-beam limit lays on the correction of the optics imperfections (section 2.2). The larger than expected vertical dispersion can be reduced and the optics irregularities (β -beating and phase advance asymmetries) corrected by insertion quadrupole adjustment (of the order of 1 ‰) and calibration file update. In general, improvements of optics measurements and correction schemes seem to yield a significant potential gain in luminosity. Beside this, an automatic equalization of the bunch currents is expected to contribute to a higher LEP luminosity. Such a system, called beam current equalizer¹⁸, has been developed and allows to balance the bunch intensities to within about 10 μ A. It is based on periodic reading (every SPS cycle) of the actual bunch currents and the adequate control of the subsequent injection from SPS to individual bunches; for those with a current higher than a chosen reference, injection is interrupted and when losses yield bunch currents lower than the reference, the injection is resumed.

Concerning coherent beam-beam modes, their frequencies have been recently computed for different configurations (ramping or physics) and different combinations of separations at the crossing points¹⁹. The response of all bunches to the excitation of one of them shows peaks in agreement with the calculated tunes of the modes. Interesting is the fact that the coherent vertical tune spread with separated beams is always small (the separation is independent of the energy), while the horizontal one ranges from 0.031 to 0.054 for physics and ramping configuration, respectively. This result indicates that the electrostatic separators near the odd interaction points should be operated at their field limit in order to reduce the corresponding contribution of the beam-beam forces to the coherent horizontal tune spread and confirms the previous recommendation²⁰ to vary β_x during ramping in proportion to the reciprocal of the beam energy, in order to keep the contribution of the even interaction points to this tune spread at the physics-configuration value for the whole ramp. It should improve the performance and the information gained about the mode frequencies might be used in the tune feedback-system.

5.0 Conclusions

This review of the LEP commissioning experience shows that continuous progress was made on the measurements of relevant quantities, diagnosis of involved phenomena and understanding of the physics behind them. Better control of the parameters and specific correction schemes often allowed to progressively move back the limits on the accumulated beam intensity and the luminosity. Recalling that the nominal values for total beam current (both beams) and luminosity were 6 mA and $1.7 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ at 45 GeV, the respective peak values reached in 1991, i.e. 4 mA and $1.0 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ are not so far away. Figs. 10 and 11 (Ref. 21) illustrate this statement and show the steady progress which has been achieved with respect to both the integrated luminosity over one year and the initial luminosity per physics run.

INTEGRATED LUMINOSITY 1990/1991

Fig. 10 Integrated luminosity for the LEP-operation years

Fig. 11 Maximum initial luminosity for each LEP fill

6.0 References

The progress made in understanding the observed phenomena is shared by many colleagues, whose names appear for most of them in the following reference list.

1. J. Billan et al., Measurement of the LEP Coupling Source, Proc. EPAC 90, Vol. 1, p. 258, June 1990.
2. G. Guignard, The General Theory of All Sum and Difference Resonances in a 3-D Magnetic Field in a Synchrotron, CERN 76-06, 1976.
3. J.P. Koutchouk, Betatron Coupling Compensation for LEP, CERN, LEP Note 480, December 1983.
4. G. Guignard et al., Measurement and Compensation of the Solenoid Effects in LEP, Proc. EPAC 90, Vol. 2, p. 1432, June 1990.
5. J. Billan, Preliminary Results of Measurements on the Ni-Layer of the LEP Vacuum Chamber, Private Communication.
6. J.P. Gourber, G. Guignard, A. Hofmann, J.P. Koutchouk, H. Moshhammer, Compensation of Linear Betatron Coupling in LEP, Proc. EPAC 90, Vol. 2, p. 1429, June 1990.
7. L. Evans, J.P. Gourber, Private Communication.
8. J.P. Koutchouk, A New Optics for LEP, CERN, LEP Note 633, March 1991.
9. P. Collier, Dispersion Measurements in LEP, CERN, LEP Performance Note 49, April 1991.
10. D. Brandt et al., Operating LEP with a 90° Lattice. Preliminary Results, CERN, LEP Performance Note 66, September 1991.
11. D. Brandt et al., Intensity Limitations and the Impedance of LEP, Proc. EPAC 90, Vol. 1, p. 240, June 1990.
12. D. Brandt et al., Measurements of Single Bunch Stability in LEP, CERN, LEP Performance Note 35, September 1990.
13. J.C. Juillard, E. Peschardt, Longitudinal Feedback for LEP, CERN, LEP Commissioning Note 14, October 1989.
14. L.K. de Jonge, J.P.H. Sladen, LEP Mountain Range Display, CERN, LEP Performance Note 36, Sept. 1990.
15. J. Gareyte, E. Keil, G. de Rijk, F. Ruggiero, Synchro-Betatron Resonances as an Intensity Limitation Mechanism, CERN, LEP Performance Note 57, July 1991.
16. D. Brandt et al., Synchro-Betatron Resonances in LEP, CERN, LEP Performance Note 56, July 1991.
17. S. Myers, Private Communications.
18. J. Bonthond et al., The LEP Beam Current Equalizer, CERN, LEP Performance Note 43, January 1991.
19. E. Keil, Frequencies of Coherent Beam-Beam Modes, CERN, LEP Performance Note 58, July 1991.
20. G. Beetham et al., Energy Ramping in LEP, CERN, LEP Commissioning Note 2, May 1989.
21. V. Hatton, Private communication.