OPTICS PERTURBATIONS DUE TO DISCONTINUOUS REPLACEMENT OF RADIATED ENERGY

G. Guignard and Y. Marti
LEP Division, CERN,
Geneva, Switzerland

1. Summary

The synchrotron radiation loss per turn scales with the fourth power of the energy and therefore increases very rapidly when raising the LEP center-of-mass energy from 110 GeV up to a maximum of about 200 GeV. This causes the beam energies to vary by an amount as large as ± 0.3% and the e^+e^- orbits to be different [1]. Since the reflection symmetry present in LEP is destroyed by the closed-orbit distortions remaining after correction, all the optics parameters, i.e. Twiss parameters, dispersions, tunes, are slightly different for e^+ and e^- bunches. As a direct consequence, the corrected closed-orbits of the two beams are also different and, in particular, the e^+ and e^- bunches would miss each other at the interaction points if their positions were not adjusted by fine tuning of electrostatic separators. Since the effects were found to be not negligible for previous LEP versions [1], and the scaling for the new LEP configuration with the energy, the amplitude of the corrected orbits and the emittance ratio is not simple, it is necessary to recalculate these effects by numerical simulations including radiations losses and orbit correction. The aim of this paper is to give some figures concerning the consequences of these effects for the nominal conditions of the first phase of LEP as well as for two particular cases of upgraded energy.

2. Expected effects

Electrons and positrons lose energy due to synchrotron radiation and this loss is discontinuously replaced in the RF stations. Consequently, the relative energy deviations $\Delta p/p$ for electrons and positrons vary along the circumference in a sawtooth manner approximately opposite for e^+ and e^-. These variations imply that the resulting orbits X in the absence of imperfections are then modified and opposite for e^+ and e^-. The extreme orbit separation is approximately given by :

$$\Delta X_{max} = 88.5 \cdot 10^{-6} \frac{E^3 \hat{D}_x}{\rho \; n_{RF}} \qquad (1)$$

where E is the beam energy in GeV,
ρ the bending radius in m,
$\hat{D}_x$ is the maximum horizontal dispersion in m, and
n_{RF} the number of RF stations.

We study the effects for the nominal parameters of LEP at 55 GeV [2] and for two cases at higher energy. The first energy retained for the upgraded LEP is 84 GeV [3], which should correspond approximately to the highest value attainable with only two RF stations (around points 2 and 6) equipped with superconducting cavities distributed in 24 RF straight sections and delivering an accelerating field of 5 MV/m. The second energy considered for the upgraded LEP is 100 GeV [3,4], which is about the highest value attainable with a total of four RF stations in regions 2, 4, 6 and 8 equipped with the same superconducting cavities distributed in 32 RF sections. If the 60^0 lattice is adequate to cover a range of currents around 3 mA at 55 GeV, the 90^0 lattice is more appropriate for operating LEP at higher energies with currents between 3 and 6 mA [4]. On this basis, the expected orbit separations have been calculated using Eq. (1) for the three cases retained (Table 1).

Beam Energy (GeV)	55	84	100
$\lvert\Delta p/p\rvert_{max}$ ($^0/_{00}$)	4.75	16.9	28.6
Phase/cell (degree)	60	90	90
ρ (m)	3096.75	3096.75	3096.75
$\hat{D}_x$ (m)	2.22	1.202	1.202
n_{RF}	2	2	4
ΔX_{max} (mm)	5.28	10.18	8.6

Table 1 - Expected orbit separations

Since the energy deviations and the orbits are opposite for e^+ and e^-, the gradient distortions appearing in the quadrupoles and sextupoles are also opposite :

$$\Delta K_{quad} = \frac{\Delta p}{p}(s) \cdot K_{quad}(s)$$

$$\Delta K_{sext} = X(s) \cdot K'_{sext}(s) \; . \qquad (2)$$

The distortions ΔK lead to perturbations of the betatron functions $\beta(s)$, the phase advances $\mu(s)$ and the dispersions $D(s)$. These perturbations have again opposite values for e^+ and e^- and are responsible for the undesired miscrossing at the interaction points, together with alignment errors. Indeed, the closed orbits caused by random kicks and including the optics perturbations can be written [1] :

$$X_{e^\pm} = \sum_i \theta_i \frac{\sqrt{\beta^*(\beta_i \pm \Delta\beta_i)}}{2 \sin \pi Q} \cos(\pi Q - \mu_i \mp \Delta\mu_i) \qquad (3)$$

where θ_i are the dipole kicks due to misalignments, β^* is the β-value at the crossing point, and $\Delta\beta_i$ and $\Delta\mu_i$ are the optics perturbations mentioned above.

3. Numerical simulations

Numerical simulations are needed to calculate the optics perturbations associated with the energy deviations in the presence of misalignments and after the correction of the orbit; the orbits are generated by random imperfections and we perform statistical calculations based on 10 machines. The PETROC program [5] was used for the simulation; the input corresponds to the content of the LEP parameter database versions dev. 4.0 and 4.3, level 2. The r.m.s. values retained for positioning errors and field dispersions are :

- for bending magnets : horizontal displacement 0.14 mm, tilt and twist 0.24 mrad, field dispersion 0.0007;
- for quadrupoles : planimetric alignment 0.14 mm, vertical alignment 0.14 mm, tilt and asymmetry 0.24 mrad, field dispersion 0.0005;
- for monitors : measurement errors 0.6 mm;
- for correctors : field and setting errors 0.5 Gm.

The optics parameters have been calculated for the cases mentioned in Sect. 2 (i.e. 55 GeV with 60^0 per cell, 84 GeV and 100 GeV with 90^0 per cell) before and after orbit correction in the absence of radiations, and after correction for radiating electrons and radiating positrons.

The differences between e^+ and e^- have been calculated for the dispersion, the twiss parameters, tunes and orbits; statistical calculations have been performed to obtain the average, the standard deviations and the maximum values of these differences mainly at the crossing points. Results are in Tables 2, 3 and 4.

4. Discussion of the results

Table 2 shows the differences between electrons and positrons for the optical parameters. Let us first consider the 60^0 lattice at 55 GeV. The maximum horizontal orbit separation obtained over 10 machines is 5.695 mm in good agreement with the corresponding value of Table 1. At the crossing points, the horizontal and vertical beam separations do not exceed about 30 μm and 10 μm respectively, while the differences in β* are smaller than ~ 18 mm and ~ 4 mm as compared with the nominal values of 1.75 m and 7 cm. The phase advance differences between two experimental interaction-points remain smaller than 0.012 and 0.033 in the two planes. Finally, the horizontal and vertical dispersion deviations at the crossing points have maximum values of 1.85 and 1.20 mm respectively, while the tunes differ by less than $3 \cdot 10^{-4}$. Let us then look at the results for the 90^0 lattice at 84 GeV. The maximum horizontal orbit separation of 10.9 mm agrees again with Table 1. The separations at crossing points can reach about 100 μm horizontally and 30 μm vertically, while the β* differences have maximum values of 166 mm and 14 mm (9.5 and 20%). The phase differences between IP's can be as large as 0.038 and 0.124, the dispersion deviations at crossing points reach values of 4.1 and 2.4 mm and the tunes may be separated by $4 \cdot 10^{-3}$.

The small differences between r.m.s. and maximum values of Δμ* computed at 55 and 84 GeV come from the fact that the distribution has two peaks, corresponding to the crossing points 2/6 and 4/8, where there are, or not, RF cavities. This suggests to do separate statistics for these two pairs of interaction points (Tables 3 and 4).

The results at 100 GeV for the 90^0 lattice with four RF stations are the followings. The maximum horizontal orbit separation is ~ 9 mm in agreement with Table 1. The separations at crossing points are in the worst case equal to 135 μm horizontally and 22 μm vertically. The differences in β* can reach up to 168 mm and 10 mm (i.e. 9.6% and 14%). The phase differences between two interaction-points remain very small, i.e. below 0.0063 and 0.0035, the dispersion deviations at crossing points have maximum values of 5.9 and 2.3 mm and the tunes may be separated by as much as $9 \cdot 10^{-3}$.

With four RF stations symmetrically installed around the ring, the sawtooth variation of the energy is such that the Δμ's between two successive interaction points vanish in average. Therefore, the maximum values of Δμ's are simply related to the random fluctuations around zero and remain small.

Let us then discuss the consequences on performance. At 55 GeV, the horizontal separation at the crossing point is never larger than ~10% of the nominal r.m.s. beam size [2] and this is tolerable for beam-beam force effects [6]. The vertical separation is comparable with the nominal r.m.s. beam size, but can be adjusted with the vernier of the electrostatic separators. The differences in the β*'s, in the phase advances between crossing points and in the dispersions agree with previously estimated values [7,8]. They are acceptable in terms of luminosity loss or in comparison with other perturbation effects. The tune separation is small with respect to the expected resolution in the tune measurements (i.e. $\sim 10^{-3}$).

f 1)	LEP 60^0/cell, 55 GeV			LEP 90^0 / cell, 84 GeV			LEP 90^0 / cell, 100 GeV		
	$\overline{\Delta f}$	<Δf>	$\lvert\Delta f\rvert_{max}$	$\overline{\Delta f}$	<Δf>	$\lvert\Delta f\rvert_{max}$	$\overline{\Delta f}$	<Δf>	$\lvert\Delta f\rvert_{max}$
x (mm)	-0.0735	2.046	5.695	-0.0690	3.726	10.968	-0.0540	3.076	9.168
y (mm)	-0.0003	0.0665	0.3549	-0.0004	0.314	1.584	-0.0001	0.2302	0.977
Dx (mm)	-0.3541	50.029	140.42	0.4257	129.97	464.11	0.1240	38.294	115.81
Dy (mm)	0.0714	7.1783	64.571	0.0562	27.594	119.91	0.0245	31.612	128.36
x* (mm)	0.0007	0.0155	0.0281	0.0021	0.0298	0.0775	0.0051	0.0515	0.1351
y* (mm)	0.0007	0.0024	0.0079	-0.0039	0.0136	0.0306	-0.0004	0.0101	0.0214
D*x (mm)	0.0723	0.5531	1.8488	-0.3595	1.9014	4.0845	-0.2275	2.5588	5.894
D*y (mm)	-0.1092	0.3652	1.1954	0.1140	0.9837	2.4430	0.0371	1.2158	2.311
Δμ*x/2π	-0.00002	0.0117	0.0124	0.0002	0.0334	0.0385	0.00008	0.0028	0.0063
Δμ*y/2π	-0.00001	0.0304	0.0332	-0.0004	0.1098	0.1241	-0.00052	0.0016	0.0035
Qx	-0.00007	0.0001	0.0002	-0.0003	0.0021	0.0042	-0.00085	0.00339	0.0088
Qy	-0.00006	0.0002	0.0003	0.0000	0.0009	0.0016	-0.00006	0.00059	0.0012
β*x (m)	-0.0003	0.0074	0.0184	0.0031	0.0725	0.1656	0.0025	0.0645	0.1683
β*y (m)	-0.0002	0.0010	0.0037	0.0019	0.0052	0.0138	0.0016	0.0046	0.0104
α*x	0.0398	0.0240	0.0681	0.0058	0.0258	0.0549	-0.0030	0.0140	0.0319
α*y	0.0707	0.0863	0.1716	-0.0005	0.0024	0.0046	0.0006	0.1018	0.2176

1) For each optical parameter f, Δf = f (positrons) - f (electrons).

Table 2

Average Δf, standard deviation <Δf> and extreme values $\lvert\Delta f\rvert_{max}$ of the optical parameter differences (results on 10 machines)

f 1)	LEP 60^0/cell, 55 GeV		
	$\overline{\Delta f}$	$\langle\Delta f\rangle$	$\lvert\Delta f\rvert_{max}$
x* 2/6 (mm)	0.0139	0.0092	0.0281
y* 2/6 (mm)	0.0012	0.0029	0.0079
x* 4/8 (mm)	-0.0125	0.0065	0.0249
y* 4/8 (mm)	0.0002	0.0016	0.0037
D*x 2/6 (mm)	0.2159	0.6798	1.849
D*y 2/6 (mm)	-0.2247	0.4918	1.195
D*x 4/8 (mm)	-0.0714	0.3499	0.8783
D*y 4/8 (mm)	0.0062	0.0619	0.1069
β*x 2/6 (m)	0.0012	0.0102	0.0184
β*y 2/6 (m)	-0.0004	0.0013	0.0037
β*x 4/8 (m)	-0.0018	0.0023	0.0067
β*y 4/8 (m)	-0.0001	0.0004	0.0015
Δμ*x/2π 2/6	0.0116	0.0004	0.0123
Δμ*y/2π 2/6	0.0300	0.0013	0.0332
Δμ*x/2π 4/8	-0.0116	0.0003	0.0124
Δμ*y/2π 4/8	-0.0300	0.0013	0.0331

Table 3 - Statistics for 55 GeV at crossing points with (2/6) and without (4/8) RF-cavities.

f 1)	LEP 90^0 / cell, 84 GeV		
	$\overline{\Delta f}$	$\langle\Delta f\rangle$	$\lvert\Delta f\rvert_{max}$
x* 2/6 (mm)	0.0116	0.0326	0.0775
y* 2/6 (mm)	-0.0029	0.0171	0.0306
x* 4/8 (mm)	-0.0074	0.0238	0.0683
y* 4/8 (mm)	-0.0048	0.0093	0.0204
D*x 2/6 (mm)	-0.4157	2.0612	3.893
D*y 2/6 (mm)	0.3207	1.1677	2.443
D*x 4/8 (mm)	-0.3032	1.7792	4.085
D*y 4/8 (mm)	-0.0926	0.7300	1.337
β*x 2/6 (m)	0.0031	0.0725	0.1656
β*y 2/6 (m)	0.0019	0.0052	0.0138
β*x 4/8 (m)	0.0058	0.0258	0.0550
β*y 4/8 (m)	-0.0005	0.0024	0.0045
Δμ*x/2π 2/6	-0.0335	0.0027	0.0372
Δμ*y/2π 2/6	-0.1067	0.0077	0.1268
Δμ*x/2π 4/8	0.0334	0.0027	0.0372
Δμ*y/2π 4/8	0.1067	0.0077	0.1249

Table 4 - Statistics for 84 GeV at crossing points with (2/6) and without (4/8) RF-cavities.

1) For each optical parameter f,
Δf = f (positrons) - f (electrons).

At 84 GeV, the horizontal and vertical separations are large and represent about half the horizontal beam radius (r.m.s.) and three times the vertical one. Both the vertical and the horizontal separations become intolerable. The differences in the β*'s may have effects on the luminosity, not so much because of the consequence on the beam sizes, but more likely because of the beam-beam resonances. However, since these variations are systematic, they are not as detrimental as the random asymmetries in β*'s. Taking into account that random asymmetries of ~4% induce a luminosity loss of ~5%, the systematic differences mentioned above seem tolerable. Differences in the phase advances between crossing points much larger than those expected at 55 GeV might have significant effect and this remains to be checked by simulation. Spurious dispersions of the order of 3 mm in the interaction regions can induce a non-negligible luminosity loss [8] depending on the tunes, which must therefore be carefully optimised. Tune separation of $4 \cdot 10^{-3}$ remains small with respect to $Q_s \approx 0.09$.

At 100 GeV, the horizontal and vertical separations represent more than half the horizontal beam size and twice the vertical one [4]. Again, both the vertical and the horizontal separations are not acceptable.The differences in the β*'s seem tolerable, using the same arguments as above, but this remains to be verified. Due to the presence of four RF stations distributed around the experimental points, the phase differences should have tolerable effect on the luminosity loss. Spurious dispersion in interaction regions and tune separation are larger in this case than at 84 GeV. Therefore, an optimum choice and a good control of the tunes are necessary, to avoid a non-negligible luminosity loss.

5. Conclusions

An important issue of the present work is the fact that both the horizontal and vertical separations of the two beams due to discontinuous replacement of radiated energy are too large for energies above the maximum energy of LEP phase 1. Consequently, fine steering of the two beams using electrostatic plates appears necessary in both planes at those energies in every interaction point. The effect of residual dispersion can likely be kept below a tolerable level by tune optimisation, but it remains to be checked if the large phase perturbations are not detrimental for the performance of the upgraded LEP with two RF stations.

References

1) M. Bassetti, Effects due to the discontinuous replacement of radiated energy in an electron storage ring, Proc. 11th Int. Conf. on High Energy Acc. (1980) 650.
2) G. Guignard, Parameter list for LEP Version 13 Phase 1, LEP Parameter Note 9 , revised 17.11.86.
3) P. Bernard, H. Lengeler and E. Picasso, Upgrading of LEP energies by superconducting cavities, CERN/LEP-DI/86-29 (1986).
4) E. Keil, LEP at 200 GeV c.m. energy, CERN/LEP-TH/87-02 (1987).
5) G. Guignard and Y. Marti, PETROC User's Guide, CERN/ISR-BOM-TH/81-32 (1981).
6) S. Myers, Simulation of the beam-beam effect for e^+-e^- storage rings, LEP Note 362 (1982).
7) J.P. Koutchouk, The imperfections of the LEP V13 Twiss parameters and their corrections, LEP Note 536 (1985).
8) J.P. Koutchouk, Estimation and correction of the spurious dispersion in LEP V13, LEP Note 530 (1985).