

# CONSEQUENCES OF THE DISCONTINUOUS REPLACEMENT OF RADIATED ENERGY ON THE PERFORMANCE OF LEP 200

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**Abstract** Owing to synchrotron radiation, electrons and positrons circulating in a storage ring lose energy almost uniformly along the arcs of the machine, while this radiated energy is replaced only by a few localized RF-stations. Therefore, even for a machine without imperfections, the orbits of electrons and positrons are different: the maximum orbit separation scales with the cube of the particle energy and is inversely proportional to the number of RF-stations. Here we present some tracking results showing the consequent reduction of dynamic aperture in the case of LEP, for different combinations of particle energy and number of RF-stations. The conclusion is that, with four RF-stations symmetrically installed around the ring, there is no appreciable reduction of dynamic aperture and, therefore, no deterioration of the machine performance up to a particle energy of 100 GeV. With only two RF-stations, however, the aperture of the standard LEP lattice with  $90^\circ$  phase advance per cell is reduced by nearly 50% above 70 GeV. We also analyse the strong dependence of this reduction of dynamic aperture on the choice of machine tunes, discussing the example of a modified  $90^\circ$  lattice whose aperture is reduced only by 20% at 100 GeV, with two RF-stations.

## 1 Introduction

As a consequence of the discontinuous replacement of radiated energy by a few localized RF-stations, the relative momentum deviation of the particles  $\delta = \Delta p/p$  has a sawtooth variation along the circumference of a storage ring. In the case of LEP,  $|\delta|_{max}$  ranges from 0.001 in phase 1 (i.e., around 55 GeV with two RF-stations) to  $0.014/n_{RF}$  at 100 GeV, where  $n_{RF}$  is the number of RF-stations. For a machine without imperfections, this sawtooth variation and the resulting closed orbit have the same periodicity of the RF-system and are approximately opposite for electrons and positrons [1]. The same is true also for the gradient distortions induced in quadrupoles and sextupoles, which lead to optics perturbations and thus to a potential deterioration of the machine performance.

In presence of alignment and field errors, the reflection symmetry of the LEP layout is destroyed and an overlapping between  $e^+$  and  $e^-$  bunches at the four interaction points is no longer guaranteed. For example, at 84 GeV with only two RF-stations (around points 2 and 6), the horizontal and vertical separations at interaction would be of about half the horizontal beam radius and three times the vertical one, respectively [2]. Since the situation is similar at 100 GeV, with four RF-stations, fine steering of the two beams using electrostatic plates appears necessary in both planes for energies above the maximum energy of LEP phase 1.

Among the consequences of the optics perturbations resulting from the discontinuous replacement of radiated energy [2, 3], those which can most seriously affect the machine performance are:

1. A possible reduction of dynamic aperture, caused by the fact that the chromatic correction scheme is optimized without

taking into account radiation effects (since the gradient and closed orbit distortions of electrons and positrons have opposite signs).

2. Systematic asymmetries in the betatron phase advances between successive interaction points. These systematic asymmetries, which can lead to a loss of luminosity through the beam-beam interaction, disappear in the case of four RF-stations, symmetrically installed around the four interaction points.

By numerical tracking, here we investigate the reduction of dynamic aperture for the standard  $90^\circ$  LEP lattice, as well as the dependence of this effect on the choice of machine tunes. Taking into account also the possible luminosity loss caused by systematic asymmetries in the phase advances between successive interaction points, these tracking results provide a basis for the determination of the maximum LEP energy which can be reached by only two RF-stations.

## 2 Tracking results for the $90^\circ$ lattice

We consider six combinations of increasing energy and different number of RF-stations, namely 55, 65, 73 and 84 GeV with 2 RF-stations and 84 and 100 GeV with 4 RF-stations, corresponding to possible scenarios of energy upgrading from LEP phase 1 to LEP phase 2 as discussed in Ref. 4. Although, in practice, the whole energy range will not be covered by a single LEP lattice, in order to obtain more homogeneous results we investigate the dynamic aperture of a lattice with  $90^\circ$  phase advance (LEP200C, see Ref. 5), having betatron tunes  $Q_x = 95.42$  and  $Q_y = 95.35$ . Compared to the original  $90^\circ$  lattice for LEP phase 1 (B1T1H, with  $Q_x = 94.35$  and  $Q_y = 98.2$ , see Ref. 6), this lattice has longer RF-sections for the installation of superconducting-cavity equipment, while the different choice of tunes is dictated by aperture constraints at injection in the high-beta insertions.

As usual, we track particles with different initial conditions over 400 turns (corresponding to twice the longitudinal damping time at 55 GeV), assuming full coupling (i.e. vertical emittance equal to half of the uncoupled horizontal emittance) and including synchrotron oscillations; tracking starts at a low-beta interaction point, where  $\beta_x = 1.75$  m and  $\beta_y = 0.07$  m, and the initial betatron slopes and longitudinal displacement of the particle trajectories are always assumed to be zero. Moreover, the initial energy deviation and the initial horizontal and vertical betatron displacements are always positive. Since we want to compare tracking results with and without the effect of radiation, the RF voltage and phase lag have to be adjusted in order to keep the synchrotron tune constant (and approximately equal to 0.1). On the other hand, at high energy the RF-bucket is reduced and corresponds to a maximum momentum deviation  $\delta$  well below 2%, which is the value usually considered in the discussion of dynamic aperture. Therefore, in order to artificially enhance the maximum stable amplitude of synchrotron oscillations, tracking

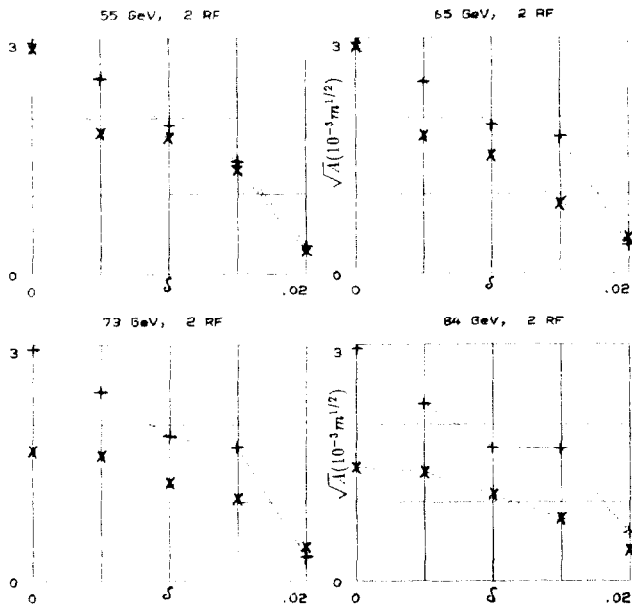


Figure 1: Dynamic aperture versus the relative momentum deviation for L200C with two RF-stations: the crosses refer to the case with radiation effects included.

is performed with a harmonic number  $h = 15660$ , corresponding to half the LEP harmonic number.

In Figs. 1 and 2 we show the results of tracking for LEP without errors: the plus signs refer to the case without radiation, while the crosses have been computed with the RADIATE option of the program MAD [7]. In both cases, the symplectic option LIE3 has been used, since it allows to reproduce previous results obtained by different tracking programs. Indeed we should stress that the only effect of radiation retained in the simulation (and allowed by MAD) is the modification of the closed orbit; the particle motion around this closed orbit is still assumed to be symplectic, since radiation damping and quantum fluctuations are not taken into account.

From the results of Figs. 1 and 2, we can draw the following conclusions:

- The relative reduction of dynamic aperture, with 2 RF-stations, is more pronounced when the beam energy is increased from 55 to 65 GeV and then from 65 to 73 GeV; at higher energy there seems to be a saturation effect, as can be seen by comparing the last two plots of Fig. 1, corresponding to 73 and 84 GeV, respectively.
- The reduction of dynamic aperture is not inversely proportional to the number of RF-stations. In particular, the dynamic aperture of LEP with 4 RF-stations (which is practically the same at 84 and at 100 GeV) is much larger than the corresponding aperture with 2 RF-stations. As shown by the plots of Fig. 2, the situation at 84 or 100 GeV with 4 RF-stations is comparable with that at 55 GeV with 2 RF-stations.

Therefore, if a simple scaling law exists for the reduction of dynamic aperture (for example at a fixed value of  $\delta$ ), it can not be the same as the scaling law for the maximum closed orbit separation, namely the reduction of dynamic aperture does *not* seem proportional to the cube of the particle energy and it is *not* inversely proportional to the number of RF-stations.

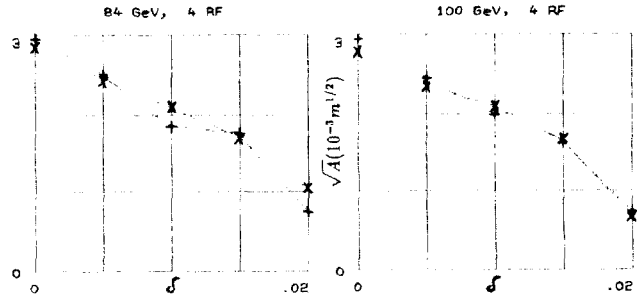


Figure 2: Dynamic aperture versus the relative momentum deviation for L200C with 4 RF-stations.

Lattice	$Q_z$	$Q_y$	$\sqrt{A} (10^{-3} m^{1/2})$		E (GeV)
			no rad	rad	
L200C (90°)	95.42	95.35	2.9	1.4	84
B1T1H (90°)	94.35	98.20	2.4	1.6	84
B1T1L (60°)	70.35	78.20	4.2	3.4	73
B1T2L (60°)	70.42	78.35	4.4	3.9	100
B1T2H (90°)	94.42	98.35	3.1	2.5	100

Table 1: Dynamic aperture at  $\delta = 0$  for different LEP lattices in the case of two RF-stations: without radiation (no rad) or including radiation effects (rad) at various energies.

### 3 Tune dependence of the reduction of dynamic aperture

In order to investigate the tune dependence of the reduction of dynamic aperture in the case of two RF-stations, in Table 1 we report the aperture at  $\delta = 0$  with and without radiation effects for different LEP lattices, both with 90° and with 60° phase advance per cell (for a description of the original 60° lattice B1T1L and of the lattice B1T2L with new tunes, see Ref. 8 and 9, respectively). At 84 GeV, the reduction of dynamic aperture of the standard 90° lattices goes from 30% (for B1T1H) to 50% (for L200C). On the contrary, the 60° lattices show a better behaviour: in particular, the reduction of dynamic aperture for the lattice B1T2L remains below 15% even at 100 GeV. Although such a low sensitivity to radiation effects can partly depend on the weaker sextupole strengths (corresponding to a larger dispersion in the regular cells), the new tunes of the lattice B1T2L are likely to be the main explanation of its good performance.

To check this hypothesis, we must recall that, owing to radiation effects, a machine without imperfections has the same periodicity of the RF-system. Therefore, since we consider the case of two RF-stations, the tunes of B1T2L are *not equivalent* to those of L200C, because of their different integer parts (modulo 2). In order to obtain a 90° lattice with tunes equivalent to those of B1T2L, we have slightly modified the lattice B1T1H (which is suited for LEP phase 1) by rematching the low-beta insertions: the dynamic aperture of this new lattice (denoted by B1T2H in Table 1) is reduced only by 20% at 100 GeV. This supports our conjecture and shows the strong dependence of such radiation effects on the choice of machine tunes.

In Fig. 3, we show more extensive tracking results corresponding to the new lattice B1T2H. Contrary to the results of Figs. 1 and 2, they have been obtained by assuming a more realistic value (1/10) for the ratio between vertical and horizontal beam emittances and include also aperture limitations associated with the physical dimensions of the beam pipe in the arcs ( $\pm 65$  mm

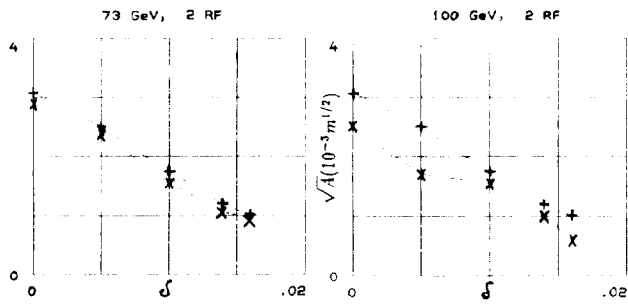


Figure 3: Dynamic aperture versus the relative momentum deviation for BIT2H with 2 RF-stations.

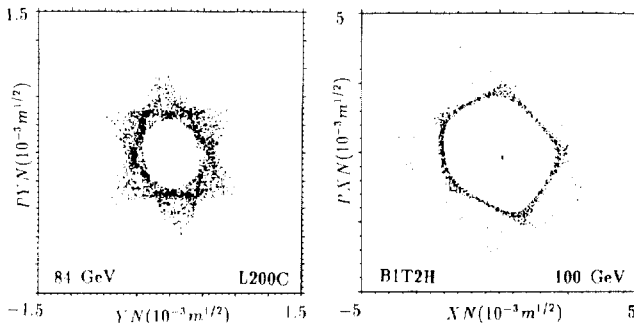


Figure 4: Phase-space plots showing the stability border with 2 RF-stations for L200C at 84 GeV and for BIT2H at 100 GeV.

horizontally and  $\pm 35$  mm vertically). Since around 100 GeV the longitudinal damping time becomes of the order of 50 turns, particles which are lost after one or two hundreds turns can still be considered as stable: this eliminates a few 'holes' in the range of stable initial amplitudes, which would otherwise reduce the dynamic aperture at large values of  $\delta$ .

Finally, Fig. 4 shows two phase-space plots in the vertical and horizontal betatron planes, representing the stability border in the case of L200C at 84 GeV and of BIT2H at 100 GeV, respectively: both plots include radiation effects with two RF-stations and correspond to  $\delta = 0$ . These plots have been obtained by tracking a single particle, undergoing a weak artificial anti-damping (with characteristic time of  $10^4$  turns). The dynamic aperture of L200C is limited vertically by a third order resonance, while that of BIT2H is limited horizontally by a fifth order resonance. The amplitudes at which these resonances occur and the shape of the stability border depend on the choice of machine tunes.

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