LOW EMITTANCE LATTICES FOR LEP

Y. Alexahin*, P. Beloshitsky*, D. Brandt, W. Herr, J.M. Jowett, M. Meddahi, G. Roy, A. Verdier,
CERN, Geneva, Switzerland

Abstract

In 1997 LEP will enter its third phase and will be operated at energies well above 90 GeV. In order to reach the required luminosities at these higher energies, i.e., to reach the maximum beam-beam tune-shift parameter, an optics with a small horizontal emittance is desirable. Such a lattice must have a dynamic aperture sufficient to guarantee the beam life time. Several lattices with different phase advances per cell have been developed for this purpose and the reasons for these particular choices are explained. The relative merits of these different solutions as well as the experience gained both in dedicated experiments and in using these lattices in regular operation during 1996 are discussed.

1 INTRODUCTION

LEP was originally designed for cell phase advances, $\mu_{x,y}$ of 60° and 90°. At beam energy $E = 45\,\mathrm{GeV}$, a 90° optics allowed the machine to be operated at the beam-beam limit. Above 90 GeV, this would require larger bunch intensities than can be achieved at present. For flat beams of k_b equal bunches of N particles, the luminosity is

$$\mathcal{L} = \frac{N k_b f_0 \gamma \xi_y}{2 r_e \beta_y^*}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right) \qquad (1)$$

where $\gamma = E/mc^2$, f_0 is the revolution frequency, r_e the classical electron radius and ξ_y the usual vertical beam-beam strength parameter. In the absence of horizontal blow-up effects, the RMS horizontal beam size is determined by the emittance, $\sigma_x^* = \sqrt{\beta_x^* \epsilon_x}$, while the vertical size σ_y^* is determined by beam-beam and other effects.

Since $\xi_y \propto N\beta_y^*/(E\sigma_x^*\sigma_y^*)$, a low emittance (high phase-advance) lattice or a lower value of β_x^* allows the beam-beam limit to be reached at high energy with lower intensity.

For flat beams, (1) shows that the luminosity depends only on ξ_y and β_y^*, the vertical beta-function at the interaction point. The luminosity is independent of $\xi_x \propto N\beta_x^*/E{\sigma_x^*}^2 = N/E\epsilon_x$. However, since ξ_x should itself not exceed a maximum value (presently $\xi_x \lesssim 0.03$ in LEP), it might be necessary to increase ϵ_x when N/E is large enough.

The minimum value, $\beta_y^* \simeq 5\,\mathrm{cm}$, is determined by the stability of the low beta quadrupoles which produce unmanageable orbit drifts if β_y^* is too small. Accordingly, in order to maximise ξ_y, the only free parameters are ϵ_x, β_x^* and σ_y^*. The vertical beam size σ_y^* is limited by our ability to correct the vertical closed orbit distortion, the betatron coupling and the vertical dispersion at the IPs. The minimum value of β_x^* is limited by the background due to the large value of β_x in QS1 and the correction of the non-linear horizontal chromaticity. Experience in LEP has shown that with $\epsilon_x = 46\,\mathrm{nm}$, a value of $\beta_x^* \simeq 2\,\mathrm{m}$ produces an acceptable background. Thus, keeping the horizontal beam size σ_x constant in the second, horizontally focusing, quadrupole from the IP (QS1), we see that the minimum of β_x^* scales with ϵ_x, a further advantage of low emittance lattices. Furthermore, since the low beta insertions generate strong chromatic aberrations which have to be corrected by the arc sextupoles, the sextupoles should be arranged in pairs separated by an odd multiple of π. Horizontal phase advances of 90°, 108° and 135° have been considered.

2 SITUATION AT THE END OF 1995

At that time, just before the increase in beam energy from 'LEP1' to 'LEP2', both theoretical work and experimental observations had been accumulated for the three options mentioned above. It was generally agreed that tracking calculations of the dynamic aperture were the best available tools to evaluate the high energy optics. The dynamic aperture of LEP is ultimately limited by the radiative beta-synchrotron coupling instability (RBSC) [1]. However the derivatives of betatron tunes with amplitude are useful indicators [2] that some combination of resonance phenomena and RBSC may limit it sooner. For example, experiments with the $(135°, 60°)$ optics [3, 4] were difficult because of the large horizontal detuning $\partial Q_x/\partial W_x$[1] that rapidly moved the tune towards the integer.

Tracking calculations indicated that, above 90 GeV, the dynamic apertures of both the $(90°, 60°)$ and the $(108°, 60°)$ optics were insufficient, mainly because of the large cross-detuning term $\partial Q_y/\partial W_x$[4, 5]. Instead, a $(108°, 90°)$ optics (with lower $\partial Q_y/\partial W_x$) was recommended for high energy. All predictions of dynamic aperture, including those of larger dynamic aperture for a prototype $(108°, 90°)$ optics, had been tested experimentally [6].

On the other hand, the $(108°, 60°)$ optics had been fully commissioned in machine development and was ready for operation. Similar development for the $(108°, 90°)$ optics would have required a re-cabling of the sextupoles (into 2 instead of 3 SD families) incompatible with the operational $(90°, 60°)$ optics. For 1996, it was therefore decided to operate LEP with a $(108°, 60°)$ optics (at 80.5 and 86 GeV)

[1]By convention, these derivatives are quoted with respect to the Courant-Snyder amplitude variables, $W_{x,y}$, equal to *twice* the canonical action variables.

* Visitors from PPL JINR, Russia

and to complete the development of the $(108°, 90°)$ optics for higher energies.

3 DETUNING WITH AMPLITUDE

The first derivatives of the tunes with respect to amplitude are presented in Table 1 for several LEP optics. Small values are generally better but it should be kept in mind that the tune-variations may become quite non-linear at amplitudes well within the dynamic aperture.

μ_x	μ_y	$\frac{\partial Q_x}{\partial W_x}$	$\frac{\partial Q_y}{\partial W_y}$	$\frac{\partial Q_x}{\partial W_y}$
$60°$	$60°$	-0.7	-1.9	-6.5
$90°$	$90°$	1.0	0.6	-14.2
$90°$	$60°$	1.8	18.7	-28.7
$108°$	$60°$	22.4	70.3	-78.7
$108°$	$90°$	25.1	16.7	-16.9
$108°$	$36°$	19.3	12.3	2.1
$102°$	$90°$	11.3	10.2	-16.2
$135°$	$60°$	-157.7	7.6	7.6

Table 1: First derivatives of the tunes with respect to amplitude at the closed orbit for various choices of the arc-cell phase advances. The units are $10^3\mathrm{m}^{-1}$.

From this point of view, the $(60°, 60°)$ optics (used in LEP operation at 45.6 GeV from 1989–91) is an excellent candidate, except that its emittance is too large at high energy. At the other extreme, the very large (negative) $\partial Q_x/\partial W_x$ of the 135°/60° optics ruled it out for operation. Table 1 also shows that all 108° optics have a rather large horizontal detuning in common. With a typical working point $Q_x \simeq 102.25$, this can bring large-amplitude particles onto the imperfection-driven resonance $3Q_x = 307$. As already mentioned, both the $(90°, 60°)$ and the $(108°, 60°)$ optics have a large cross-term $\partial Q_y/\partial W_x$ which is mainly responsible for the insufficient aperture predicted at high energy. The $(90°, 90°)$ optics originally proposed for LEP2 remains a strong candidate. It was dropped from consideration in recent years because $\mu_y = 90°$ is unfavourable for polarization and its emittance is not so small as with $\mu_x = 108°$. Nevertheless calculations show that it has the largest dynamic aperture.

4 LIFETIME AND DYNAMIC APERTURE

As described in detail in previous papers [5, 6, 7], two methods are commonly used to measure the acceptance of LEP:

Kick method: A bunch is given a single kick whose amplitude is increased until about 50 % of the bunch population is lost. The corresponding amplitude is an estimate of the horizontal dynamic aperture and has been compatible with predictions from tracking in all cases studied [7].

Phase space inflation: The horizontal emittance of the beam is increased by reducing the RF frequency (and, consequently, the damping partition number, J_x) until the lifetime reaches a value of one hour. This provides an estimate of the maximum emittance with which the machine can be operated. *If the particle dynamics is essentially linear* (and weakly-damped), direct application of the elementary quantum lifetime formula can be used to estimate the dynamic aperture from this emittance.

Under such conditions, which amount in practice to the absence of strong resonances and "anomalous" non-gaussian beam tails, both methods agree quite well.

Such conditions *do not hold* in, e.g., the $(108°, 90°)$ optics at high energy where the motion is strongly non-linear because of resonances and strong radiation effects. With the kick method, resonances manifest themselves as a partial loss at a certain kick amplitude [5] (corresponding to the location of the high-order fixed points). In deterministic tracking (with "radiation damping" but no quantum fluctuations [1]) of imperfect machines, these amplitudes were found to be stable and are therefore included in the dynamic aperture. At higher amplitudes, the losses decreased before finally rising rapidly at a larger amplitude corresponding to the dynamic aperture.

With the inflation method, it was found in 1996 that the lifetime dropped when the resonance amplitudes were sufficiently populated (usually when they corresponded to about 6σ of the distribution of the beam core). A tentative explanation of the reduced lifetime in terms of enhanced diffusive transport by the resonances has been proposed [8].

Thus, good dynamic aperture is not in itself sufficient to provide good lifetime. It may lead to an over-estimate of the emittance that can be accommodated in the machine, as measured by phase-space inflation.

5 MEASUREMENTS IN 1996

In June 1996, LEP was started up with a $(108°, 60°)$ optics. During the initial period of collisions at 45 GeV (required for the calibration of the detectors), lifetime deteriorated as soon as the bunch intensity exceeded $I_b \simeq 200\,\mu\mathrm{A}$. The available aperture was measured and found to be about 20 % smaller than predicted. Given the pressures of time and other conditions unrelated to beam dynamics, the optics was abandoned without actually having been tested at high energy and the "fall-back" $(90°, 60°)$ optics was commissioned. This optics behaved much as predicted and record performance was achieved at 80.6 and 86 GeV.

Towards the end of the period, the sextupoles were recabled and the $(108°, 90°)$ optics was given its first full test. At 45 GeV, similar lifetime problems to those observed with the $(108°, 60°)$ lattice were experienced. It should be noted that, with both 108° optics, it was the first time that LEP was operated with $\xi_y < \xi_x \gtrsim 0.03$. So far, it is not understood whether the observed strong blow-up of the horizontal beam size was related to the absolute value of ξ_x or another mechanism. Apart from these problems at 45 GeV, the $(108°, 90°)$ optics was used in operation at 86 GeV for the last three weeks of the 1996 period and yielded peak luminosities about 60 % of the best achieved with the $(90°, 60°)$ optics. The main experimental observations can be summarised as follows:

- The maximum ϵ_x measured with the inflation method was about 30 % smaller than predicted and smaller than needed for operation above 90 GeV.
- Third and higher order resonance effects were clearly seen in the beam centroid motion following kicks.
- The missing acceptance was correlated with the presence of enhanced beam tails. Enhanced diffusive transport by the imperfection-driven resonance $3Q_x = 307$ has been invoked to explain the tails [8]. Further resonances are important at larger amplitudes.
- The vertical beam size remained larger than expected from the usual compensation of linear betatron coupling. This anomalous vertical beam size has now been interpreted as a consequence of the proximity of the working point to the synchro-betatron resonance $Q_y - 2Q_s = 96$; it is reproduced in tracking with quantum fluctuations. This feature is much weaker on the $(90°, 60°)$ optics.

These unexpected results have been extensively analysed. The reduced lifetime does not appear to be related to any systematic errors in the model of the machine or the particle dynamics. Systematic non-linear resonances can also be excluded. The only plausible explanation is that the problem is related to the presence of strong resonance islands located at large amplitudes which, in the case of all 108° optics, are easily reached by the particles because of the horizontal detuning with amplitude $\partial Q_x/\partial W_x$. The straightforward behaviour of the $(90°, 60°)$ optics as expected is consistent with this.

6 FUTURE OPERATION

On the basis of the experimental results in 1996, it has been decided to use a $(90°, 60°)$ optics for operation in 1997. At 92 GeV, ϵ_x will be reduced by increasing the damping partition number J_x. However, the motivation for a low emittance lattice remains strong since the latter technique requires more longitudinal dynamic aperture and so reduces the maximum energy attainable with the given RF voltage. As far as low emittance lattices are concerned, three possible counter-measures are presently under study:

Minimize the resonance driving terms (mainly 3rd order). A scheme with some independent sextupoles is under study. A new working point (less sensitive to synchro-betatron resonances) will also be tried.

Reduce the horizontal detuning. A scheme with octupoles is being studied. However, hardware considerations render its implementation impossible before 1998.

An optics with smaller horizontal detuning. Given our present understanding, such a solution seems attractive. As a result of preliminary studies, a $(102°, 90°)$ optics is a very promising candidate. It reduces $\partial Q_x/\partial W_x$ by more than a factor of two (see Table 1) while the related increase in emittance would only be 10 $\%$ as compared to the 108° case. Admittedly, such a solution would only be compatible with a single sextupole family in the horizontal plane (hardware constraint) which would not allow β_x^* to be reduced. In fact, a 90° optics (with modified J_x and squeezed β_x^*) would yield a comparable if not better performance than this new lattice. For this reason, a $(90°, 90°)$ solution might regain the attraction it lost in 1993 because of polarization.

7 CONCLUSION

The dynamic apertures of both the $(90°, 60°)$ and the $(108°, 60°)$ optics were predicted to be insufficient above 90 GeV, mainly because of the large cross-detuning term $\partial Q_y/\partial W_x$. Following experimental tests and extensive calculations for imperfect machines in 1995-96, the $(108°, 90°)$ optics was retained as the ultimate candidate for high energy. Operation in 1996 with this optics has shown that the presence of strong imperfection-driven resonances combined with a large horizontal detuning (common to all 108° optics) resulted in the build up of tails which reduce the practical stability region to values lower than required above 90 GeV. Operation in 1997 will resume with a $(90°, 60°)$ optics. Increasing the horizontal damping partition number J_x should reduce the horizontal emittance enough for both background and performance considerations. In parallel, efforts will continue towards developing an improved low emittance lattice. These efforts will be shared between finding cures to the problems of the $(108°, 90°)$ optics (minimize the resonant driving terms and reduce the detuning with amplitude) and developing a new $(102°, 90°)$ optics that could be an attractive alternative from 1998 onwards. In case of difficulties, a $(90°, 90°)$ optics would have to be seriously re-considered.

8 REFERENCES

[1] F. Barbarin, F.C. Iselin, and J.M. Jowett, Proc. 4th European Part. Acc. Conf., London, 1994, p. 193.

[2] S. Kamada, CERN LEP Note 297 (1981).

[3] Y. Alexahin et al.,"Low Emittance Lattice for LEP", Proc. Particle Accelerator Conf., Dallas, 1995.

[4] A. Verdier,"Cross Anharmonicity", AIP Conf. Proc. 344, (1994), p.269.

[5] Y. Alexahin, CERN SL-95-110 (AP) (1995).

[6] J.M. Jowett, et al., "The Dynamic Aperture of LEP at High Energy", Proc. Eur. Part. Acc. Conf, Barecelona, 1996.

[7] F. Ruggiero, "Dynamic Aperture for LEP2", Proc. 5th Workshop on LEP Performance, Chamonix 1995, p.164.

[8] J.M. Jowett, "Non-linear Resonances: Predictions, Effects and Measurements", Proc. 7th Workshop on LEP Performance, Chamonix 1997, p.76.