TAILORING THE PERFORMANCE OF LEP

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SUMMARY

Experience gained with existing e^+e^- storage rings and the accumulation of understanding derived from theory and simulation allow more accurate prediction of the performance of future machines like LEP. We describe the relation of luminosity to other quantities of interest to the machine users, such as energy spread, beam sizes or polarization. For example, the maximum event rate on a narrow resonance may not correspond to the condition of maximum luminosity. Partial control of beam parameters is available through damping partition number variation, coupling adjustment, wigglers, etc. but a proper estimation of the necessary operating conditions must include a self-consistent, realistic treatment of the beam-beam effects which also determine performance. The established correlation between theory and simulation of the beam-beam effect in several regimes has been exploited in the search for good working points. Single particle stability (dynamic aperture) has been improved at the same time.

1. INTRODUCTION

This paper summarises recent work concerned with reliably foretelling, controlling and improving the performance of the LEP machine. Although such exercises for an uncompleted machine give many hostages to fortune, it is hoped, and expected with some confidence, that the information accumulated in the operation of existing e^+e^- colliders, improved theoretical understanding and better simulation programs, permit one to make realistic predictions. In any case, there is the obligation to provide the best possible information on the luminosity and the conditions in which it is obtained.

Clearly it would be futile to try to predict performance in anything other than the fairly reproducible conditions of a well run-in machine with a good closed-orbit correction and steps taken to suppress those instabilities for which cures are known; this should be the case after one to two years of operation.

In this paper we first describe the most important "knobs" that we shall exploit for optimising the performance, then discuss strategies for choosing good tunes and their verification. Finally we summarise the procedure for calculating the relationship between the controllable beam parameters and performance which leads to different modes of operation.

2. CONTROLLABLE PARAMETERS

It is intended to exploit to advantage the possibility of varying damping partition numbers through small shifts of the RF frequency and thereby the closed orbit in LEP. For definiteness, we assume that the vertical damping partition number $J_y = 1$ and the radial and longitudinal ones may be varied in the nominal range

$$0.5 \leq J_x = 3 - J_z \leq 2.5. \quad (2.1)$$

In view of the importance of the vertical beam height in determining the luminosity the betatron coupling compensation scheme [1,2] will play an important role. In terms of the coupled horizontal and vertical emittances ϵ_{xc} and ϵ_{yc} , the coupling is characterised by the parameter $\kappa \equiv \sqrt{\epsilon_{yc}/\epsilon_{xc}}$ where the uncoupled horizontal emittance (without wigglers) is

$$\epsilon_{x0} = \epsilon_{xc} - \epsilon_{yc} \propto E^2/J_x \quad (2.2)$$

and the natural beam sizes at the interaction point are

$$\sigma_x^* = \sqrt{\epsilon_{xc}\beta_x^*}, \quad \sigma_y^* = \sqrt{\epsilon_{yc}\beta_y^*}. \quad (2.3)$$

The compensation scheme should permit the control of the emittance ratio within the range

$$0.08 \leq \kappa \leq 0.2 = \sqrt{(\beta_y^*/\beta_x^*)} \quad (= \text{"design coupling"}) \quad (2.4)$$

The 8 dipole wigglers [3] have recently been reconfigured [4] to provide additional flexibility. Four of them (the so-called "emittance wigglers") are in positions of high dispersion so that their excitation increases emittances, energy spread, damping rates and polarization rate. The others ("damping wigglers") are in positions of nominally zero dispersion and therefore do not affect the emittance significantly while having similar effects on the other quantities mentioned. Since ϵ_{x0} can be kept above $168 \pi \text{ nm}$ at all energies, the emittance wigglers are sufficient to maximise the potential luminosity while all wigglers can halve the damping times at injection or speed up the Sokolov-Ternov polarization mechanism without the undesirable side-effect of an excessive emittance increase, e.g. with all wigglers excited to maximum field and $J_x = 1$, ϵ_{x0} never exceeds $78 \pi \text{ nm}$ for $E \leq 50 \text{ GeV}$.

3. WORKING POINTS

Performance depends critically on the values of the betatron tunes Q_x , Q_y and synchrotron tune Q_s . Here we refer to the "unperturbed tunes" for incoherent motion of a zero-amplitude particle; tune-shifting effects are included in terms of the free tune-space required around these tunes. Studies [5] have been made to determine the most promising tunes for LEP operation. During ramping, the synchrotron tune is held constant at a value given essentially by the requirement of good quantum lifetime at top energy, $Q_s = 0.085$, say, although values up to 0.116 are possible. Then Q_x and Q_y are chosen to avoid several sorts of resonance

$$\begin{aligned} k_1 Q_x + k_2 Q_y + k_3 Q_s &= p \quad (\text{imperfection resonances}) \\ &= pS \quad (\text{systematic resonances}) \end{aligned} \quad (3.1)$$

(k_1, k_2, k_3, p integers; $S=4$, the superperiodicity). The LEP lattice (with 60° phase advance per cell in the arcs) allows both Q_x and Q_y to be varied over a range of 4 integers. Of those resonances affecting single-particle dynamics, it is of course essential to stay away from low order betatron resonances ($k_3=0$) and their synchrotron sidebands ($k_3 \neq 0$) although the systematic components of some of these are removed by built-in lattice periodicities [1]. The consequences of the interplay of the many resonances of order greater than 3, driven mainly by interference among sextupoles and quadrupoles, can only be assessed by tracking studies and the consequent dynamic aperture. Animations of tracked orbits suggest that frequency-locking phenomena associated with difference resonances ($k_1 k_2 < 0$) of order 7 and higher may be partly responsible for bounding the particles' motion on time-scales of several tens of turns. In this way, and by virtue of the radiation damping, a large region of chaotic phase space is assimilated into the usable dynamic aperture.

Since the momentum acceptance of the LEP lattice is always limited by the descent of Q_y into a half integer stopband for negative momentum deviation δ , Q_y must be kept at least 0.3 units above an integer to guarantee an acceptance $\delta = \pm 2\%$. The weak momentum-dependence of Q_x imposes no special constraints.

When intense beams are in head-on collision, strongly driving those resonances with both k_1 and k_2 even, sufficient free tune space must be available for the familiar "footprint" of incoherent beam-beam detuning. The overall size of this depends on the effective tune-shift parameter, ξ (see Section 4). With separators at the 4 unused interaction points, the tune-spread in the beam is then 4ξ , swamping all other tune-shifts at moderate betatron amplitudes. Since low-order resonances are least dense near the coupling resonances (CRs) of the main diagonal

$$Q_x - Q_y = p_1, 2Q_x - 2Q_y = p_2, \dots \quad (3.2)$$

it is profitable to place the tune close to it. The linear CR (first member of (3.2)) is compensated but higher-order CRs (e.g. $k_1=2, k_2=-2$) are driven by the beam-beam force. However from the perturbative analysis of [6] it emerges that large amplitude beating of single particles can be prevented by choosing the tune below and at least $S\xi/8$ away from the diagonal (equivalent to keeping the "footprint" from overlapping the CR). The synchrotron sidebands of (3.2) are not expected to cause trouble, since the ratio of beta function to bunch length, β_y/σ_z is not sufficiently small [7].

Separators in the long insertions cause the system of 4 bunches per beam to decouple into two independent systems of 2 bunches per beam, whence the threshold for coherent dipole oscillations [8] is comfortably high if the fractional part of each tune is < 0.5 . Although dipole and quadrupole excitations can be avoided, linear stability theory [9] shows that excitation of higher coherent modes is inevitable.

Taking confidence from previous successful predictions of the simulation [10,11], we found the best tunes for the latest LEP configuration without repeating the long series of simulation runs which had been made for LEP Version 11 (with collisions in all 8 interaction points among other differences).

Since simulation [12,5] confirms the applicability of the CR theory, we chose tunes just below the main diagonal. This resonance apart, the luminosity appears more sensitive to the vertical tune value. Existing results indicated that the most auspicious Q_y in the range of the LEP optics was around $Q_y = 78.30$, implying $Q_x = 70.35$. Other promising values were rejected for one or other of the reasons given above.

After a fine scan of the tune-dependence [13] in this region, it was found that it did indeed provide greater luminosity. The largest saturation value, $\xi = 0.039$, was found at $Q_x = 70.42$, $Q_y = 78.35$ which was adopted as the new tune value. However the improvement over previous values of $\xi = 0.030$ is due in part to the reduction of the number of interaction points. Changing the integer part of Q_y [13] has confirmed the virtue of working close to the main diagonal. No beam-beam excited resonances up to order 7 intersect the beam-beam tune spread (Fig. 1).

When the LEP lattice was rematched to the new tunes, its dynamic aperture was substantially improved [13] compared to that obtained with the old tune values [1] and an identical chromaticity correction scheme. Not only was the momentum acceptance increased - as one might expect - but the maximum stable betatron amplitudes showed a 20% improvement, throwing the stability boundary outside the mechanical acceptance of

the arcs. This is believed to be due to a benign influence of the CR. Particles can pass through regions of chaotic motion but then lock on to the resonance which reintroduces a degree of regularity, and therefore stability, into their motion. Once on the resonance, their tune shifts tend to be along the diagonal itself.

4. BEAM-BEAM EFFECT AND LUMINOSITY

To provide realistic estimates of the luminosity in conjunction with the values of the parameters discussed in Section 2, a realistic characterisation of the beam-beam induced blow-up is required. Whereas at low intensity the beam size is determined simply by the balance between quantum excitation and radiation damping, this equilibrium is disturbed by new transport effects in high current colliding beams. To reach the "beam-beam limit", it is necessary to adjust beam sizes so that the unperturbed tune-shift parameters ξ_{x0} , ξ_{y0} - as calculated through the standard formulae via the synchrotron radiation integrals - have somewhat larger values (0.06, say) which get reduced to the effective limiting value by the non-linear forces, reflecting the inflation of transverse (mainly vertical) beam dimensions. Since the values of the radiation damping times play an important role in the new dynamic equilibrium [14], their values are not those which would give the inflated beam size at low intensity.

With this in mind, we have adopted the following simplified prescription for luminosity estimates (for more details see [15]). Having calculated zero-current beam sizes and hence ξ_{x0} , ξ_{y0} , the "luminosity", L_0 , in the absence of blow-up, can be calculated by standard formulae. The effective tune-shift parameter ξ is then given by a distillation of simulation and phenomenology:

$$\xi = \xi [1 - \exp(-\min(\xi_s, \xi_{y0})/\xi)] [1 - \Delta_0/\Delta], \quad (\Delta \geq 1.48 \cdot 10^{-4}) \\ = 0, \quad (\Delta < 1.48 \cdot 10^{-4}) \quad (4.1)$$

where $\Delta = (k_b f_0 \tau_y)^{-1}$ is the damping decrement [14] and $\xi_s = 0.06$; $\xi = 0.0643$ and $\Delta_0 = 3.20 \cdot 10^{-5}$ are fitting parameters, chosen to reproduce the performance at the selected working point. The luminosity is then given

by [12]

$$L = L_0 \xi / \xi_{y0} \quad (4.2)$$

exhibiting the familiar behaviour [12,16] at small ξ_{y0} and large Δ :

$$\xi / \xi_{y0} \rightarrow 1 \text{ as } \xi_{y0} \rightarrow 0 \text{ and } \Delta \rightarrow \infty, \text{ i.e. } L \propto I^2 \quad (4.3)$$

and saturation for $\xi_{y0} = \xi_s$ ($L \propto I$).

5. ADAPTATION OF PERFORMANCE

Since the beam current, I , is limited at injection energy [1] performance must be estimated with I constant; here we assume a nominal total $I = 3$ mA in 4 bunches.

Maximum luminosity, L , is obtained in the familiar way (Fig. 2): keep $\xi_{x0} = \xi_{y0} = \xi_s$ when possible, i.e. maintain design coupling and adjust $J_x \propto E^3$ to make $\epsilon_{x0} \propto E^{-1}$. The limits on J_x variation, (2.1), mean that, below $E = 37$ GeV, wigglers have to be used to increase ϵ_{x0} . Above $E = 63$ GeV, ϵ_{x0} cannot be made small enough (a larger I is needed to reach the beam-beam limit in both planes); however L can be increased by decreasing κ (reducing the beam height) until $\xi_{y0} = \xi_s$ or minimum κ , (2.4), is reached. The aperture limitation is encountered at about 75 GeV.

Besides this, there is interest in concentrating luminosity on particular centre-of-mass energies e.g. to provide maximum illumination of a narrow resonance in the particle spectrum or reduce background. One may consider either minimising the energy spread, ϵ_{rms} , (keeping $J_x = 0.5$) or, more interestingly, maximising the ratio L/ϵ_{rms} which determines the luminosity per unit centre of mass energy at the centre of the distribution [15]. In the latter case (Fig. 3), thanks to the full coupling variation (2.4), ϵ_{rms} is held at its minimum value ($J_x = 0.5$) from 37 GeV up to 49 GeV whereupon J_x variation is exploited to maintain $\xi_{y0} = \xi_s$ right up to 72 GeV. Remarkably, the total luminosity is

almost identical to that of Fig. 2, despite the quite different machine conditions (a difference emerges only with higher I). With flat beams, the vertical beam size is much the more important in determining L .

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Fig. 3 - Maximum L/ϵ_{rms} conditions

Fig. 2 - Maximum luminosity conditions

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