MORE BUNCHES IN LEP

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Abstract LEP has been designed to operate with 4 bunches in each beam. In view of the physics interest, we consider the possibility of increasing the number of bunches in order to provide a higher luminosity at the Z^0-resonance. Unwanted head-on collisions can be avoided by horizontal separation in a four-fold "pretzel" scheme analogous to the one employed in CESR and requiring additional electrostatic separators, working independently of those already foreseen. Residual beam-beam effects are minimised by selecting an optimum combination of bunch number and optics. Modifications of the standard LEP optics and RF system are necessary. We discuss the performance which can be expected with such a scheme, criteria for evaluating it and the factors which limit it.

1 Introduction

In its initial configuration—with 4 bunches per beam and single bunch currents limited around 1 mA—LEP is expected to provide its four detectors with a high luminosity (around $1\text{-}2 \times 10^{31}$ cm^{-2}sec^{-1}) at 46 GeV, the energy of the Z^0 peak in the e^+e^- cross section. In parallel with the energy upgrade of the machine, there is the possibility of pushing the luminosity still higher at the Z^0. It has been pointed out [1] that such a measure would extend the domain of accessible physics, notably through the copious production of beauty mesons, and reduce the running time needed at the Z^0.

With well-known assumptions, the luminosity of an e^+e^- storage ring is given by

$$L = \frac{k_b f_0 N_b^2}{4\pi\sigma_x^* \sigma_y^*} = \frac{k_b I_b (E_0/m_e c^2)\xi}{2er_e\beta_y^*}, \tag{1}$$

the second member of which applies at the beam-beam limit. For the purposes of this paper, we shall use the nominal parameters: energy $E = 46.5$ GeV, bunch current $I_b = 0.75$ mA, $\beta_y^* = 7$ cm at the interaction points (IPs), limiting beam-beam parameter $\bar\xi = 0.04$, and refrain from discussing potential increases in L through improvements of these values. However it is important to note that the main limitation on the performance of LEP is expected to be the limit on I_b imposed by the transverse mode-coupling instability at injection energy. The I_b storable falls some way short of the 2.5 mA needed to fill the machine aperture at the beam-beam limit. With $k_b = 4$ bunches per beam, (1) yields $L = 1.7 \times 10^{31}$ cm^{-2}sec^{-1}.

In view of the success of the many-bunch scheme at CESR[2], we have taken a fresh look at the feasibility of colliding more than 4 bunches in LEP. To increase L this way we have to avoid unwanted head-on collisions in places other than the 4 detectors. The largest k_b compatible with use of the storage cavities on the room-temperature copper RF system is $k_b = 8$ and earlier discussions [3,4] focussed on schemes with a local separation bump in mid-arc. (LEP is already equipped with local vertical separation systems at the 4 unused odd-numbered IPs). With the advent of the superconducting RF system, we can contemplate many more bunches in a "pretzel" scheme where the electron and positron beams have separate orbits throughout the arcs of the machine but common orbits in the interaction regions.

2 Implementation choices

In a pretzel scheme, electrostatic or RF-magnetic separators are used to produce a closed orbit distortion in each arc; in linear approximation, a half-integer number of betatron wavelengths between separators guarantees common e^+e^- orbits in the interaction region. The minimum bunch separation S_b is determined by the lengths of the parts of the ring where the orbits are common.

In LEP, the scheme is subject to the following constraints:

- The beams must collide at the 4 even-numbered IPs.

- The beams should be separated throughout as much of the machine as possible, especially in the arcs.

- To avoid driving synchro-betatron resonances, there should be no closed-orbit deviations in the RF cavities (Such effects could not be compensated for *both* beams simultaneously.)

- It is undesirable to disrupt the existing layout of magnets and other hardware any more than absolutely necessary.

The RF cavities in LEP are immediately adjacent to the dispersion suppressor (DISS) which is full of bending magnets. Without changing the machine geometry, the only way to install separators is by removing the last few cavities before DISS. In practice, this means that the pretzel scheme cannot be implemented until some superconducting RF cavities are installed and some, at least, of the copper system is removed. The remaining copper cavities can run with many bunches if the storage cavities are not used. The requirements of a pretzel scheme can be accommodated in the future configurations of the LEP RF system [5].

Figure 1 shows the essentials of our proposed pretzel scheme in which the bunch separation must satisfy

$$S_b \gtrsim 2 \times \text{distance from IP to DISS} = 490\,\text{m}. \tag{2}$$

Hence the number of bunches $k_b = C/S_b < 54$, where C is the circumference, and must be an *even* factor of the RF harmonic number $k_b = 31320 = 2^3 \cdot 3^3 \cdot 5 \cdot 29$ to ensure collisions at the 4 even IPs. The possibilities are listed in the first column of Table 1. (Intermediate bunch numbers are possible by filling only some of e.g. 36 evenly-spaced buckets. However this does not help to avoid the "bad" collision points discussed below.)

Although separation requirements for flat beams are less with vertical separation [6], there is less vertical aperture. More seriously, the pretzel orbits would be off-centred vertically in sextupoles and the resulting betatron coupling would be difficult to compensate for both beams simultaneously. Although we may contemplate colliding round beams, one may as well then separate horizontally.

We have obtained better results with the high-tune version of the LEP lattice (smaller emittances are available in the event that the single-bunch current is low). The optics has, of course, to be adapted to satisfy the phase-advance requirements of a pretzel scheme. Happily, a great deal of flexibility and modularity was built into the LEP lattice design [7].

3 Beam-beam effects with separated bunches

In the arcs of the machine, the e^+ and e^- beams have separate orbits, $x_+(s) \simeq -x_-(s)$ (the orbits are not exactly symmetric
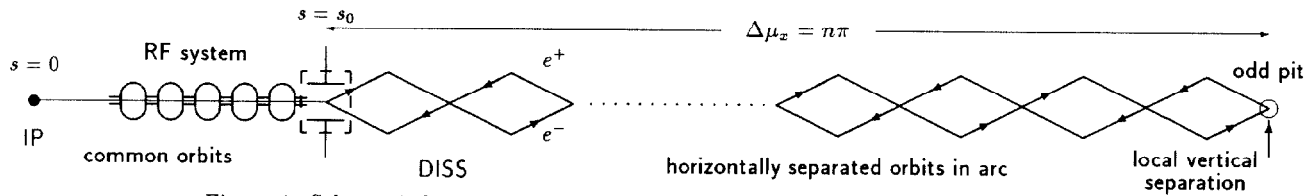
Figure 1: Schematic layout of the pretzel scheme in one octant of LEP (not to scale).

around $x = 0$ because of accumulating edge-effects in bending magnets, etc.), where

$$x_+(s) \simeq \frac{\Delta p_x}{p_0} \sqrt{\beta_x(s)\beta_x(s_0)} \sin\left(\mu_x(s) - \mu_x(s_0)\right) \qquad (3)$$

and Δp_x is the transverse momentum kick imparted to the e^+ beam by the separator at $s = s_0$. Pairs of bunches undergo parasitic—or wanted—encounters at azimuths $s_j = nC/2k_b$, $j = 0, \ldots, 2k_b - 1$ where they are separated by a distance $X(s) = x_+(s) - x_-(s)$ horizontally. The beam-beam strength parameters (effective linear tune-shifts) due to transverse field gradients are

$$\xi_x^{(j)} = \frac{N_b r_e \beta_x(s_j)}{2\pi(E/m_e c^2)} \int_0^\infty \frac{\exp\left(-\frac{X(s_j)^2}{2\sigma_x(s_j)^2 + t}\right) dt}{(2\sigma_x(s_j)^2 + t)^{3/2}(2\sigma_y(s_j)^2 + t)^{1/2}} \qquad (4)$$

$$\xi_y^{(j)} = \frac{N_b r_e \beta_y(s_j)}{2\pi(E/m_e c^2)} \int_0^\infty \frac{\exp\left(-\frac{X(s_j)^2}{2\sigma_x(s_j)^2 + t}\right) dt}{(2\sigma_x(s_j)^2 + t)^{1/2}(2\sigma_y(s_j)^2 + t)^{3/2}} \qquad (5)$$

where the local beam sizes are

$$\sigma_x(s_j) = \sqrt{\varepsilon_x \beta_x(s_j) - \eta_x(s_j)^2 \sigma_\varepsilon^2}, \qquad \sigma_y(s_j) = \sqrt{\varepsilon_y \beta_y(s_j)}.$$

Using (3) and the leading term of the asymptotic expansion of (4) and (5) for $X(s_j)/\sigma_x(s_j) \to \infty$, gives

$$\xi_x^{(j)} \sim \frac{N_b r_e m_e E}{8\pi\beta_x(s_0)\left[\Delta p_x \sin\left(\mu_x(s) - \mu_x(s_0)\right)\right]^2}, \qquad \frac{\xi_y^{(j)}}{\xi_x^{(j)}} \simeq \frac{\beta_y(s_j)}{\beta_x(s_j)},$$

showing that, if the separation is large at all crossings, then compensation of these "long-range beam-beam effects" will be simplified if the distribution of tune-shifts and optical perturbations is kept roughly constant by varying the separator fields $\propto \sqrt{E}$. Clearly, we wish to maximise $\beta_x(s_0)$ and (except for the odd IPs) avoid crossings where $\mu_x(s_j) - \mu_x(s_0) \simeq n\pi$.

Because of the oscillatory dependence of β_x, β_y, η_x and $x_\pm$ on s and the high-tune of LEP, the residual beam-beam tune-shifts are the result of a kind of beating among these various "waves" and the bunch pattern.

The total tune spread in the beams is approximately

$$\Delta Q_{x,y} \simeq 4\bar\xi + \frac{1}{2}\sum_{j=1}^{2k_b-1} {}' \xi_{x,y}^{(j)}.$$

where the prime indicates that the sum excludes the even IPs and, if $k_b/2$ is even, the odd IPs. It can amount to $\simeq 0.2$ in colliding beam mode with $k_b = 4$. During injection and ramping there is little contribution from the IPs, but we must ensure that $\Delta Q_{x,y} \lesssim Q_s \simeq 0.1$ [6]. The parasitic encounters in the pretzel scheme should not change this too much. More refined criteria await a full-scale simulation of all effects but we can note that the beam-beam interactions of well-separated bunches are more akin to well-distributed optical perturbations than the non-linear effects at small separations.

In the following, we give results only for colliding beam conditions but conditions after injection have also been checked. However the accumulation process itself has not yet been simulated.

k_b	$\Delta'Q_x = \sum_{j=1}^{2k_b-1}{}' \xi_x^{(j)}$	$\Delta'Q_y = \sum_{j=1}^{2k_b-1}{}' \xi_y^{(j)}$
2	0.	0.
4	0.	0.
6	0.056	0.014
8	0.0003	0.00006
10	0.005	0.0097
12	0.108	0.025
18	0.072	0.016
20	0.367	2.602
24	0.108	0.026
30	0.133	0.396
36	0.111	0.030
40	0.550	4.165

Table 1: Parasitic beam-beam tune-shifts as functions of the number of bunches; I_b and other parameters kept constant.

4 Performance of a pretzel scheme in LEP

We have studied the potential performance of various pretzel schemes in LEP using the program MAD [8] to generate the pretzel orbits and optics. The program WIGWAM [9] is interfaced to MAD via the TWISS file: in this application, it evaluates the synchrotron radiation integrals, optimises the electron beam parameters, computes (4) and (5) at the parasitic crossings and provides graphical output in many forms, e.g. Figure 3.

Separators are taken to be installed in the last RF cell just before the DISS; although $\langle\beta_x\rangle$ is minimised in the RF section, we still get a reasonable $\beta_x(s_0) \simeq 60$ m.

In the following, the electric field and effective length are

$$E_x = 0.8\,\text{MV/m}, \qquad L_{\text{SEP}} = 8\,\text{m}$$

(or equivalent for RF magnetic separators), giving a pretzel orbit with amplitude $\hat x_\pm = 11$ mm. Electrostatic separators based on the LEP design should be able to go a factor 2 beyond this.

Optimum number of bunches

First we examine the variation of parasitic beam-beam tune-shifts with k_b. Results obtained with the natural beam sizes (no wigglers, $J_x = 1$) are shown in Table 1. The unacceptably large tune-shifts occurring e.g. for $k_b = 40$ are due to two "bad" crossings per octant where $x_\pm(s_j)$ are small and $\xi_y^{(j)} \simeq 0.2$.

The most promising of the larger bunch numbers is $k_b = 36$ which is used for the remainder of this paper.

Minimum separation

Now we use the damping partition and wigglers to meet the usual prescription for maximum luminosity [9] (doubling the natural emittance in this case). Figure 2 shows the results of varying the separator field to vary $\hat x_\pm$.

Figure 3 shows details when $E_x = 0.8\,\text{MV m}^{-1}$ and

$$\sum_{j=1}^{2k_b-1}{}' \xi_x^{(j)} \simeq 0.15, \qquad \sum_{j=1}^{2k_b-1}{}' \xi_y^{(j)} \simeq 0.11$$
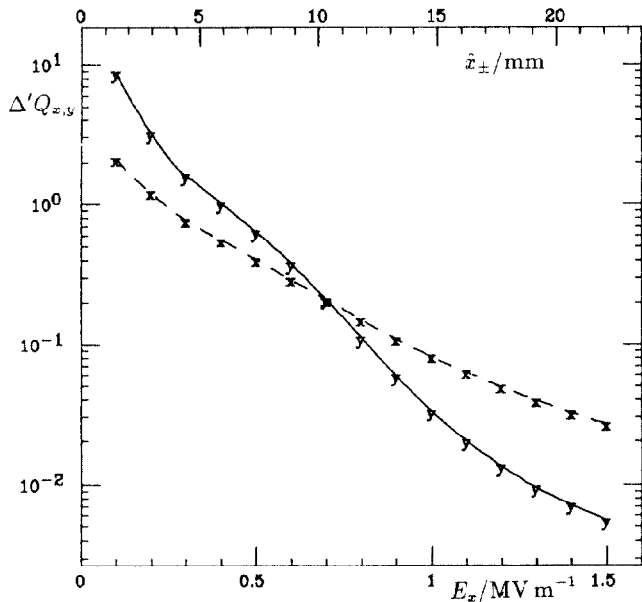
Figure 2: Residual tune-shifts as functions of separator field.

Figure 3: Orbits, optics, beam-sizes and parasitic tune-shifts in a 36-bunch pretzel. "Error bars" show beam sizes.

which should be acceptable. In this case, the aperture requirement at the peaks of the pretzel orbit in certain horizontally focussing quadrupoles is

$$\hat{x}_{\pm} + 10\sigma_x \simeq 11.7 + 10 \times 2 \simeq 32\,\text{mm}$$

Since the horizontal aperture of LEP ($\pm 65\,$mm) is relatively large, it is unlikely that we will have to reduce the emittance in order to keep the beam tails clear of vacuum chamber walls and there appears to be scope for still higher luminosity—or a safety margin—through increased $\hat{x}_+$ and higher I_b.

The dynamic aperture calculations done up to now for LEP are not valid with these closed orbits and ought to be repeated to fully justify these assertions. Experiments with global beam-bumps can be performed in the initial period of LEP operation and should elucidate the question of just how much aperture can be used.

According to the usual LEP luminosity model [9], some vertical beam-beam blow-up will occur to reduce $\bar{\xi}$ to 0.036, yielding a peak luminosity

$$L \simeq 1.4 \times 10^{32}\,\text{cm}^{-2}\text{sec}^{-1}$$

If I_b can be increased much beyond 0.75 mA then it will probably be necessary to reduce the number of bunches. It appears that there will be an upper limit to the luminosity of LEP (a few $10^{32}\,\text{cm}^{-2}\text{sec}^{-1}$ at the Z^0).

With these parameters, the radiated beam power (neglecting higher-order mode (HOM) loss) is

$$P_{\text{beam}} = 2k_b I_b U_0 = 7.4\,\text{MW} \tag{6}$$

which can easily be supplied after an initial installation of superconducting cavities [5]. There is scope for luminosity enhancement at higher energies also but the total current which can be stored for a given RF power decreases $\propto E^{-4}$.

Apart from separators and RF, a number of other machine components (e.g. various cooling systems, the beam position monitor system, feedback systems, trim power supplies, injection kickers and septa) may require modifications or upgrading. The LEP cavities can be equipped with couplers to provide adequate HOM damping to counter multi-bunch instabilities. Careful ramping procedures will be needed to maintain the conditions for pretzelled beam stability throughout a ramp. Integrated luminosity depends critically on injection rate and beam-gas lifetime; clearly these must both be pushed to the maxima feasible.
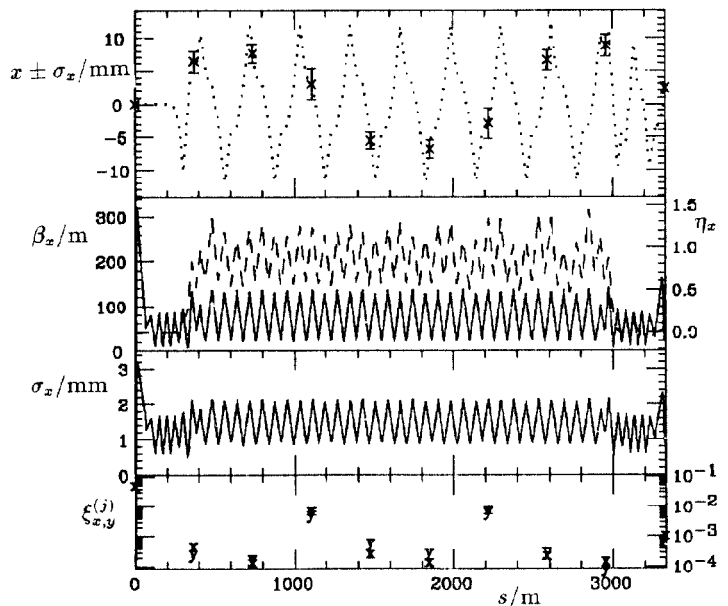
5 Conclusions

With the help of a pretzel scheme, it should be possible to push the peak luminosity of LEP at the Z^0 some way beyond $10^{32}\,\text{cm}^{-2}\text{sec}^{-1}$.

A pretzel scheme can be implemented once some of the copper RF is removed and some superconducting RF installed. It also requires the installation of electrostatic or RF-magnetic separators and upgrades to a number of other pieces of hardware. Since there are no really drastic changes to the machine it should be easy to switch to high energy LEP operation with 4 bunches.

Operation of LEP with a pretzel scheme will be considerably more complicated and much detailed work remains to be done, particularly on the optics. Experiments on displaced orbits and with many bunches (in a single beam) in the initial phase of operation will help our understanding.

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