SIMULATION OF THE BEAM-BEAM EFFECT DURING INJECTION, ACCUMULATION AND ACCELERATION IN LEP

S. Myers
CERN, 1211 Geneva 23, Switzerland

Summary

The beam-beam program[1] is used to simulate non-collision conditions for LEP. These results are used to facilitate the choice between horizontal and vertical separations at the interaction points and to quantify the required amount of separations. It is shown that in certain cases the residual beam-beam kicks during injection with separated beams can cause severe 'blow-up' in the transverse beam emittance and thereby lead to a reduction in the apparent injection efficiency. Results are also shown for transient effects which occur while the beams are brought into collision.

Introduction

In modern electron-positron storage rings where the horizontal beam rms radius (σ_x*) is much larger than the vertical one (σ_z*) the beam-beam strength parameters for zero beam separations are given by

$$\xi_{xo} = \frac{r_e i_b}{2\pi\gamma e f_{rev}} \frac{\beta_x^*}{\sigma_x^{*2}} \; ; \; \xi_{zo} = \frac{r_e i_b}{2\pi\gamma e f_{rev}} \frac{\beta_z^*}{\sigma_x^*\sigma_z^*} \quad (1)$$

where i_b is the current per bunch (A)

and f_{rev} is the resolution frequency (Hz)

In the absence of wiggler magnets and when β* remains constant with energy it is well known that σ_x* and σ_z* are directly proportional to energy. From (1) it is then clear that

$$\xi_{x,z} \propto \frac{i_b}{\gamma^3} \quad (2)$$

It is evident from (2) that if the beam-beam limit $\hat{\xi}$ is reached at a certain current at design energy then it would be greatly exceeded for the same current at injection energy. For this reason the beams are separated in the interaction regions during accumulation and acceleration. For beams separated[2] by an amount (δ) large compared with the transverse beam dimensions

$$\xi_{xs} = \frac{r_e i_b}{2\pi\gamma e f_{rev}} \frac{\beta_x^*}{\delta^2} \; ; \; \xi_{zs} = \frac{r_e i_b}{2\pi\gamma e f_{rev}} \frac{\beta_z^*}{\delta^2} \quad (3)$$

If the separations are measured in the number of horizontal σ_x* (i.e. $\delta = k_x\sigma_x^*$) equations (1) and (3) give the simple relations

$$\frac{\xi_{xs}}{\xi_{xo}} = \frac{1}{k_x^2} \; ; \; \frac{\xi_{zs}}{\xi_{zo}} = \frac{1}{k_c k_x^2} \quad (4)$$

$$\text{where} \quad k_c = \frac{\sigma_x^*}{\sigma_z^*} \gg 1$$

Equation (4) indicates that for 'optimum' coupling ($\xi_{xo} = \xi_{zo}$) and large separations then $\xi_{xs} = k_c\xi_{zs}$. It is also clear that the high values of ξ_o at injection energy can be reduced either by horizontal or vertical separations by the appropriate amount. The principal aims of this work were to specify the requirements for separations in the interaction regions. In previous electron storage ring designs it has become accepted that the beams be separated in the vertical plane by an amount equivalent to $2.5 \rightarrow 4.0\ \sigma_x$* [3,4].

In order to investigate the requirements for separations the following modes of a complete LEP cycle are investigated.

(i) Injection and Accumulation (20 GeV). Injection is assumed to be performed in the horizontal plane so as to facilitate synchrotron[5] or betatron accumulation or a combination[6] of both. For this case the β values at the interaction regions are assumed detuned by a factor of two (for complete details of all relevant parameters see ref. 7).

(ii) Static Separations of the Accumulated Beam at 20 GeV. This is the situation after accumulation and before acceleration.

(iii) Static Separations at 51.5 GeV. The beams have been accelerated and the low-β configuration tuned to its settings for physics ($\beta_x^* = 1.12$, $\beta_z^* = 0.07$).

(iv) Bringing the beams into collision at 51.5 GeV. The beam separations are exponentially decayed to 'zero'.

Two criteria may be used to specify the separation requirements:

(i) the amount of transverse blow-up caused by the residual beam-beam forces,

(ii) the ratio between the residual beam-beam tune spread and the synchrotron tune[8] (Q_s).

The latter criterion should also be included since single-beam synchro-betatron resonances have not been included in the beam-beam simulation. If the ratio between the residual beam-beam tune spread and Q_s is maintained less than unity then at least in principle synchro-betatron resonances can be avoided by suitable choice of the tune.

Simulation Results

Injection and Accumulation

For this case horizontal injection (in the presence of a strong counter-rotating beam) at an initial amplitude of $7\sigma_x$ is assumed. Figure 1 shows the evolution of the beam size (normalized to the equilibrium beam sizes in LEP). Figure 1(a) shows that with a separation of 10 σ_x* the injected beam converges towards its equilibrium size (1.0) in both planes with approximately the correct damping rate (τ = 0.40 s). The initial fast apparent 'blow-up' in the horizontal plane is caused by 'filamentation' due to the tune dependence on amplitude introduced by the residual beam-beam forces. Figure 1(b) indicates that when the horizontal separations are reduced to 7 σ_x* the beams are badly blown up and the vertical damping is lost. This sets a limit of 7 σ_x* for the required amount of horizontal separations. (The beam-beam strength parameters are ξ_{xs} = 0.0014 and ξ_{zs} = 0.0001.)

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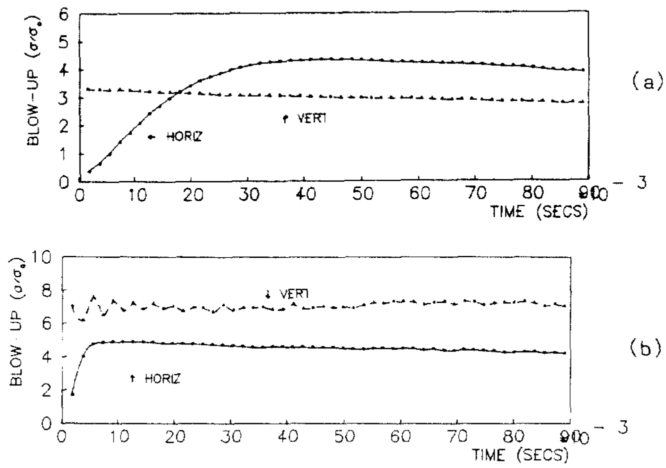

Fig. 1. Horizontal Injection with Horizontal Separations

(a) $\overline{x} = 10\ \sigma_x^*$ (b) $\overline{x} = 7\ \sigma_x^*$

Figure 2 shows similar results for vertical separations of 20 σ_z* (1.25 σ_x*) and 10 σ_z* (0.62 σ_x*). From these plots it is clear that vertical separations of 1.25 σ_x are perfectly adequate to allow efficient injection in the presence of a counter-rotating beam of design intensity.

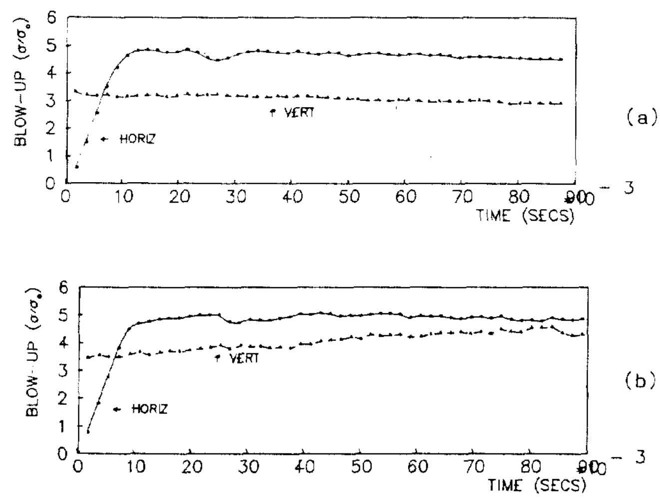

Fig. 2. Horizontal Injection with Vertical Separations

(a) $\overline{z} = 20\ \sigma_z^*$ (b) $\overline{z} = 10\ \sigma_z^* = 0.62\ \sigma_x^*$

Static Separations at 20 GeV and 51.5 GeV

In this case the two separated intense counter-rotating beams experience each other's residual beam-beam forces. Figure 3 shows the computed relative blow-up (after 1000 turns) as a function of the vertical separations at 20 GeV. The results indicate, rather surprisingly, that even very small vertical separations do not cause disastrous beam blow-up. However, it should be remembered that the LEP configuration at injection energy incorporates strong wiggler magnet excitation in order to increase the transverse damping rate. These wigglers also increase the transverse emittances so that the unperturbed beam-beam strength parameters are only ξ_{xo} = 0.062 and ξ_{zo} = 0.065 with zero separation. Similar results for horizontal separations show disastrous beam blow-up at around 2 σ_x* separation.

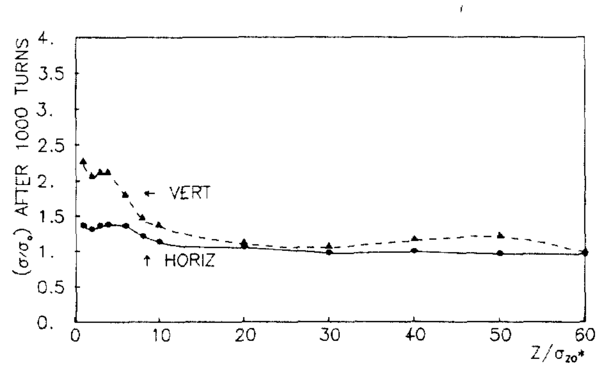

Fig. 3. Static Vertical Separations at 20 GeV.

It is clear from Fig. 3 that vertical separations of 20 σ_z* (1.25 σ_x*) completely eliminate the effect of the residual beam-beam kicks for the LEP injection configuration.

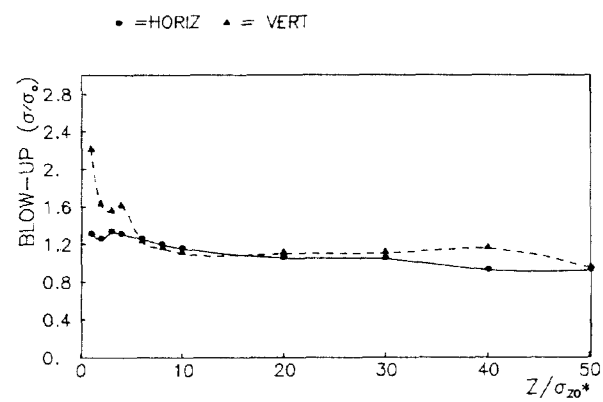

Fig. 4. Static Vertical Separations at 51.5 GeV.

Figure 4 shows the computed relative blow-up as a function of the amount of vertical separation at 51.5 GeV. There is a marked similarity with the results obtained for 20 GeV. This is almost certainly because the ξ_o in both cases are very similar.

Bringing the Beams into Collision at 51.5 GeV

It is clear from Fig. 4 that, since static vertical separations of almost any amount do not cause excessive blow-up, bringing the beams into collision even very slowly will likewise not cause excessive blow-up. This has been verified by bringing the beams into collision with a time constant of 0.25. However, Fig. 5 shows that this is not true for horizontal separations. In Fig. 5 the transient relative vertical beam size is plotted as a function of the transient horizontal separation for various exponential time decays of the separation and with an initial separation of 10 σ_x* at t = 0. It is clear from these results that a time constant of less than 0.5 ms is needed (this corresponds to 5 turns in LEP) in order to avoid vertical blow-up.

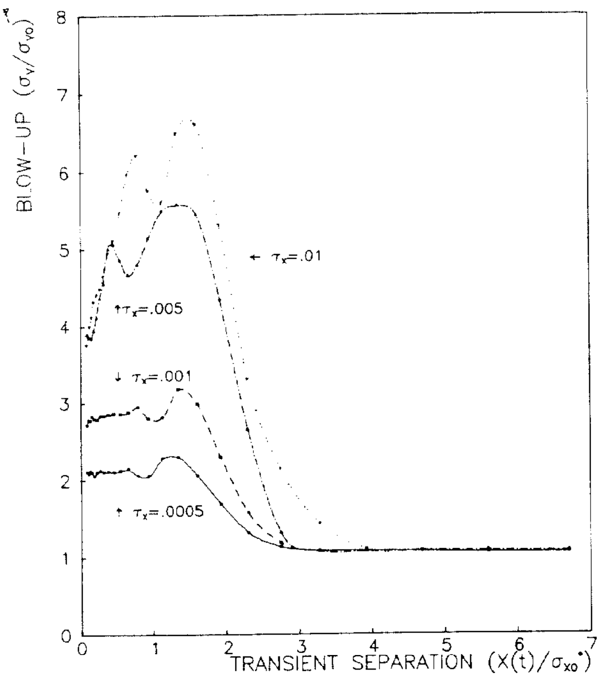

Fig. 5. Bringing beams together horizontally at 51.5 GeV.

Separation Requirements

For LEP version 12[9] the synchrotron tune is 0.1 and there are eight regions where the beams experience each other. Consequently in order to be able to avoid synchro-betatron resonances the maximum beam-beam tune spread per crossing to 0.0125. The beam-beam tune spread is approximately 0.5 times the shift (ξ). Hence the maximum residual beam-beam tune shift is

$$\xi_s = 2\Delta Q_{bb} = 0.025$$

If a factor of two is allowed for Q fluctuations, non-zero width of synchro-betatron sidebands and other uncertainties then a ξ_s of 0.0125 is obtained. Putting this limit value into the accurate equation for the residual beam-beam tune shift as a function of separation (for all LEP conditions previously cited) gives a minimum value for the required separations.

Table 1 summarizes the required separations in order to satisfy the synchro-betatron resonance criterion and also to avoid excess blow-up as predicted by simulation.

Examination of Table 1 shows that vertical separations are to be preferred for two main reasons.

(i) The required separations are significantly less. In particular, to avoid blow-up of the injected beam, vertical separations require only ~0.7 mm whereas horizontal separation requires 5.6 mm.

(ii) Bringing the beam into collision in the horizontal plane requires very fast turn-off of the electric field on the plates. This is not necessary in the vertical plane. Similar results are reported in both simulation and experiments elsewhere[10]. The ability to switch off slowly the separator plate voltage considerably eases the design and cost of the separator system[11].

Table 1. Summary of Separation Requirements

Operation mode	Criterion used	Required amount of Separation: Horizontal $\bar{x}/\sigma_{xo}^*$	Horizontal (mm)	Vertical $\bar{z}/\sigma_{zo}^*$	Vertical (mm)
Injection/ accumulation	Blow-up	10.0	5.6	20.0	0.7
	Synchro-betatron resonances	2.5	1.4	29.0	1.02
Static separation at 20 GeV	Blow-up	6.0	3.37	20.0	0.7
	SBR	2.5	1.4	29.0	1.02
Static separation at 51.5 GeV	Blow-up	4.0	1.47	6.0	0.14
	SBR	2.5	0.92	28.0	0.65

Conclusions

A comparison was made between horizontal and vertical separations for several relevant operational modes of the LEP storage ring. The results indicate that horizontal separations are technically more difficult, hence the separations should be performed in the vertical plane. It is proposed that the magnitude of the vertical separation should be equivalent to 2.0 σ_x*. This value meets comfortably the two criteria examined for all operational modes and allows some margin which may be required for future changes to the LEP design.

Acknowledgements

The author is grateful to K. Hübner who instigated the study and provided many parameters for the simulation runs, and to T. Taylor who provided the parameters for the low-β configuration.

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