Experimental Studies of Pretzel Beam Dynamics in LEP

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Abstract

The first stage of the programme to increase the luminosity of LEP by colliding more than 4 bunches per beam was implemented during 1991. Electrostatic separators were installed to create "pretzel orbits" in two quadrants of the ring, a new optics was implemented, new operational procedures were established, and numerous experimental studies of beam behaviour and differential optical effects on pretzel orbits were carried out. The results of this experimental programme settle many beam-dynamics questions relating to the feasibility of the scheme and the prospects for a future High Luminosity LEP can be considerably clarified.

1 INTRODUCTION

The "pretzel" scheme, intended to increase the number of stored bunches, k_b, and, hence, the luminosity of LEP has been described previously [1, 2, 3]. An 8-bunch scheme [4] using electrostatic separators (ZX) recuperated from the Sp$\bar{p}$S collider is being implemented now with a view to operation for physics at the Z^0 resonance in 1992. This is also seen as a step on the way to 8-bunch operation at energies beyond the W-pair production threshold. Operation with more than 8 bunches would require further changes to a variety of hardware systems.

Four of the eight electrostatic separators required for the pretzel scheme were installed for the beginning of 1991, allowing pretzels bumps to be created in two quadrants of LEP, as shown in Figure 1. With a single beam in the ring, it was possible to simulate the effect of the missing separators with corrector magnets close to their future locations. Although it did not allow 8 bunches in both beams, this configuration made it possible to carry out a range of studies related to the feasibility of the final scheme. This paper summarises the beam dynamics studies; for further details see [5]; for the separator behaviour see [6].

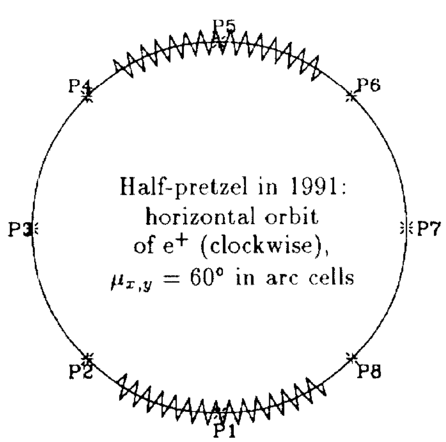

Figure 1: Pretzel orbit configuration created with 4 electrostatic separators in 1991.

For reference, we list the following bunch configurations which were studied, among others:

1. *$k_b = 1$ or $k_b = 4$ in one beam.*
2. *$k_b = 4$ in each beam, with encounters at P1–P8.*
3. *$k_b = 1$ in each beam, timed to have mid-arc encounters in (P1,P2) and (P5,P6).*

A plan to inject 3-bunch trains to provide all encounter types simultaneously was not carried out for lack of time.

2 OPTICS AND ORBITS

2.1 *The 60° pretzel optics*

Closure of pretzel orbits and the antisymmetry of the pretzel orbits [3, 4] about the odd-numbered crossing points (P1,...,P7 where there are no detectors and the beams are normally separated vertically) imposes constraints on the horizontal phase advances between the ZXs and the odd points which were not satisfied in the normal operational optics. A special pretzel optics had to be created and, in order to stay as close as possible to the operational optics (with tunes $\mathbf{Q} = (Q_x, Q_y) \simeq (70.3, 76.2)$, the phase advances around the odd points were reduced to give tunes of $\mathbf{Q} \simeq (69.7, 75.6)$. (Although the intention has always been to use a pretzel optics with $\mu_x = 90°$ per arc cell, the use of a 60° optics was considered safer, given the limited machine development time available and difficulties which had been experienced in 1990 with 90° optics.)

Since the phase advances between the dominant source of chromaticity, (the low-β insertions) and the sextupoles in the arcs were not changed, this optics was expected to have similar chromatic properties and dynamic aperture around the central orbit. Local orbit corrections could also be carried over and, indeed, helped this optics to be commissioned very quickly. Nevertheless, it is worth noting that this was the only LEP optics so far to have fractional tunes in the upper half-integer. We found no clear evidence for or against the proposition that such tunes could provide higher intensities.

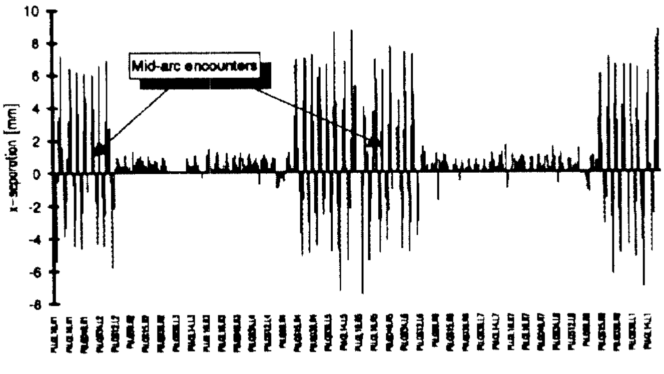

Figure 2: Horizontal difference orbit, at 20 GeV, over the whole circumference of LEP, starting at P1. Pickups are located at vertically focussing quadrupoles so the peak amplitude is a factor 1.37 larger than shown. Moreover all pickup readings have to be scaled up by a factor 1.25. The measurement was made when the separation was sufficient to allow slow but steady accumulation with single bunches encountering each other in 2 mid-arc points.

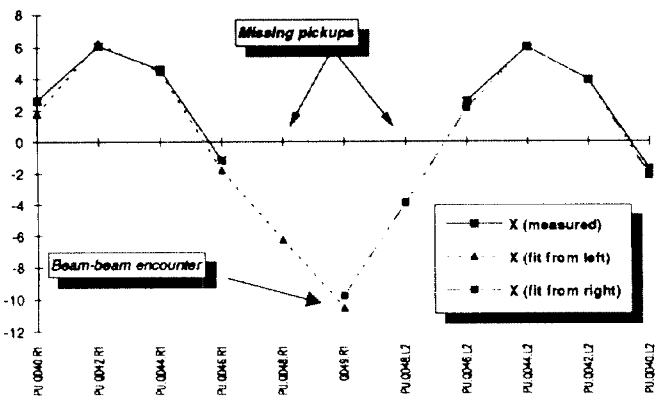

Figure 3: A detail of Figure 2, showing the horizontal difference orbit measured around a mid-arc point where e^+e^- bunches encounter each other. Two of the narrow band pickups do not give a reading because of the short interval between the two bunch passages. Nevertheless, independent fits from left and right using the computed optical functions agree with each other and show that the beams were separated by 12.5 mm at their encounter (after scaling).

2.2 Orbits at injection

Many electrostatic and magnetic pretzel orbits were created and measured [5] with single beams. Since there are just two separators for each pretzel bump, closure of the bumps has to be achieved by trimming the betatron phase μ_x within the pretzel. This was done by rematching the HIBL insertions around the odd points and proved to be very accurate. Shifts of a few degrees were generally sufficient to reduce the residual horizontal orbit to the noise level of the pickups.

Horizontal pretzel orbits were always coupled into the vertical to some extent (typically 10 % at 20 GeV) because of the coupling source in LEP (generally associated with the nickel layer on the vacuum chamber).

Figure 2 shows the difference between e^+e^- orbits in Case 3 of Section 1 in an experiment in which the separation was gradually increased from zero until accumulation of e^+ began against an existing e^- beam, the separation being estimated as about 7–8 mm or $5.5\sigma_x$ for the weak bunch. An offset of the measured orbits can be attributed to the difference in intensities of the two beams ($I_b^+ = 80\,\mu$A, $I_b^- = 190\,\mu$A).

Since there are no pickups at any of the bunch encounter points it is necessary to interpolate orbits by fitting a betatron trajectory to the measured values. Figure 3 is an example of the use of this technique to overcome the fact that the narrow-band pickups near the mid-arc cannot resolve the separate bunch passages and to obtain the orbit separation at the mid-arc point.

2.3 Ramping

Compared with the pretzel scheme in CESR [7], which has a full-energy injector, a major additional complication for LEP is the necessity to ramp two beams on pretzel orbits from the injection energy (20 GeV) to the collision energy (around 46 GeV). Adequate separation will have to be maintained at a total of 16 bunch encounter points: local vertical separation at P1–P8 and horizontal pretzel separation for the mid-arc points.

A large fraction of the machine time spent on these studies was devoted to establishing the ramp files for the pretzel optics. We followed the then standard procedure of increasing E in small steps and establishing orbit and tune corrections with the pretzels switched off. The long intervals between sessions meant that the utility of previous corrections tended to decay (because of drifts, realignments, etc.) so the result was certainly of a quality inferior to an intensively-maintained operational ramp. Moreover, no attempt was made to provide further corrections, e.g., pretzel closure, at intermediate energies. Nevertheless we were able to ramp all the beam configurations listed in Section 1 with moderate intensities ($I_b \approx 100\,\mu$A) and *negligible losses*.

Sparks occurring in one separator during some ramps did not cause beam loss.

2.4 Collisions

Following the energy ramp, the β-functions are squeezed down to their values for collisions before the bunches are allowed to collide. A value $\beta_y^* = 5$ cm was achieved with a pretzel orbits and a single beam but there was no time to re-establish it beyond $\beta_y^* = 9$ cm when we later collided the beams (Case 2 of Section 1). A brief "physics" run was made with pretzel orbits in two quadrants. In one detector, the specific luminosity was close to its normal value but the others suffered due to horizontal and vertical mis-crossings. We had partial success in improving this with some pretzel phase trims. These *horizontal* phase trims had the incidental effect of switching coherent *vertical* beam-beam oscillations off and on.

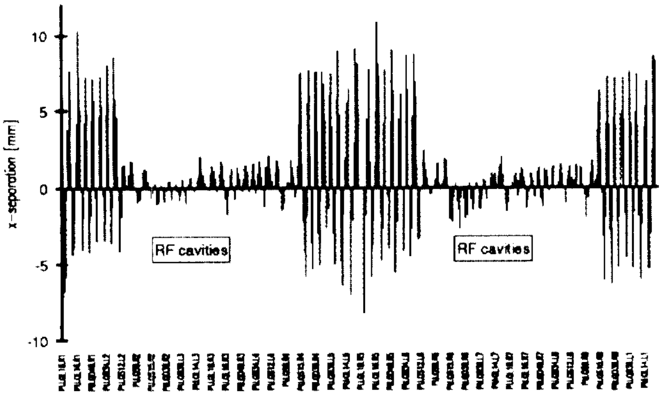

Figure 4: Horizontal difference orbit as in Figure 2. In this case there are 4 bunches colliding in P2,...,P8 and vertically separated in P1,...,P7 at 45.6 GeV. The additional separation from the "energy sawtoothing" due to the localisation of the RF system around P2 and P6 is clearly visible. The corresponding residual vertical difference had a global RMS value of 0.9 mm.

The difference orbit in Figure 4 clearly shows the deviations in the orbits due to the "energy sawtoothing" effect which produces a separation of some 2 mm in mid-arc at this energy even without the pretzel.

3 EMITTANCE

It was found that the horizontal emittances, measured with the UV synchrotron light monitors, grew with pretzel amplitude as in Figure 5. There was *no significant change in vertical emittance* either at injection or collision energies. This can be accounted for by a change in longitudinal damping partition number

$$J_\epsilon = 2 + \frac{2}{I_2} \int K_1^2(s) D_x(s) x_c(s)\, ds \qquad (1)$$

due to the dispersion and pretzel orbit in the quadrupoles. With the normal periodic dispersion the last term averages out but the pretzel orbits generate large additional components of dispersion in quadrupoles and sextupoles. The additional terms have different harmonic content [5] and cause a dependence of the type showen in Figure 5. The effect can be cancelled with an RF frequency variation.

After ramping the beams shown in Figure 2, the separation was $3.8\sigma_x$ in terms of the measured beam size but the lifetime remained around 40 h.

4 CONCLUSIONS AND OUTLOOK

It appears that LEP has sufficient aperture to support a pretzel scheme, at least up to energies of about 46 GeV. Good single-beam behaviour was found on pretzel orbits with amplitudes up to about 1 cm and lifetimes comparable to flat orbits. So far we have not succeeded in achieving sufficiently rapid accumulation on pretzel orbits but there is a clear threshold for separation at the unwanted encounters. Ramping with pretzel orbits turned out to be somewhat easier than expected. New operational procedures,

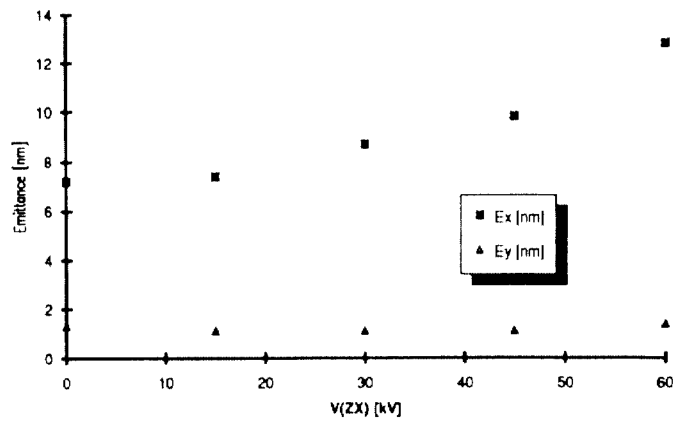

Figure 5: Emittance measured at 20 GeV as a function of pretzel separator gap voltage, V. The emittance can be fitted with an expression of the form $\epsilon_x(V) \simeq \epsilon_x(0)/(1 - aV^2)$ with $a > 0$, suggesting that $J_x = 3 - J_\epsilon = 1 - aV^2$.

some of which have now been prototyped, will be needed to correct orbits and optics and steer beams together at the collision points. It is expected that future operation with a 90° pretzel optics will help with accumulation and ramping. It remains to be seen how large a separation will be needed with high intensities. This and higher energy operation will make heavy demands on the present installation of electrostatic separators. However the results of the experiments described here give us good hope that the pretzel scheme will increase the luminosity of LEP in the near future.

In the longer term, the prospect of many more bunches, e.g., $k_b = 36$ [1, 3] remains open if the hardware investments are made. Meanwhile an 8-bunch scheme should help to increase the luminosity for LEP200 within the limits of the RF and separator systems.

Acknowledgements

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