Commissioning and Operation of the LEP Pretzel Scheme

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Abstract

From its start-up in 1989, LEP ran, as designed, with 4 bunches per beam and flat orbits. After 4 days of commissioning activity in October 1992, the regular mode of operation became 8 bunches per beam, thanks to a horizontal separation scheme of the "pretzel" type. Here we describe this transition, starting from the final stages of the machine studies which preceded it and concluding with the performance achieved by the end of 1992 and the factors limiting it. Some of the important steps were: the redistribution of betatron phase advance, minimisation of tune-splits between the beams, chromaticity changes, reduction of residual separations at the interaction points when running for physics at the Z^0 energy, optimisation of pretzel separations at injection and in collision, and equalisation of the bunch currents. A number of changes to operational procedures and instrumentation were made. It was shown that, with a suitable optics, the full beam polarization could be preserved on pretzel orbits. This allowed energy calibration by resonant depolarization and a measurement of the energy shift on pretzel orbits.

I. LEP Operation with Pretzel Scheme

Feasibility studies and preparatory machine experiments connected with the LEP pretzel scheme have been described in previous papers [1, 2, 3]. Here we report on the final commissioning of the scheme for a first period of physics data-taking. It is intended to become the regular mode of operation of LEP from now on. Considerably more detail can be found in [5].

In 1992 the full set of 8 separators was available and the 4 spare arc sextupoles were installed in non-experimental straight sections to allow a partial compensation of the tune-split between the beams due to imperfections.

The low-emittance ($\mu_x = \mu_y = 90°$ in the arc cells) optics used throughout the year was designed with the pretzel scheme in mind. Some preliminary studies [3] were made during the year to study the problems of injection into 8 bunches per beam, energy ramping and "squeezing" to the luminosity optics with $\beta_y^* = 5\,\mathrm{cm}$. Then, during one week of intense activity in October, the pretzel scheme was commissioned as the regular operational mode of LEP for the last 4 weeks of the 1992 run. The break-even point in luminosity, compared with the previous 4-bunch operation, was reached within 3 days.

Figure 1 shows the configuration of electrostatic separators for the pretzel scheme. The circumference can be divided into 4 quadrants between the experiments (even-numbered IPs), each containing a single pretzel bump with horizontal betatron phase advance $\Delta\mu_x = 20 \times 2\pi$ between the two separators. Although the main separator pairs are on the same high voltage supplies their electrode gaps can be remotely adjusted to provide some independent variation of their electric fields. (Two additional trim separators have now been installed to adjust beam separations independently at all 4 IPs in 1993 (DW in [5]).)

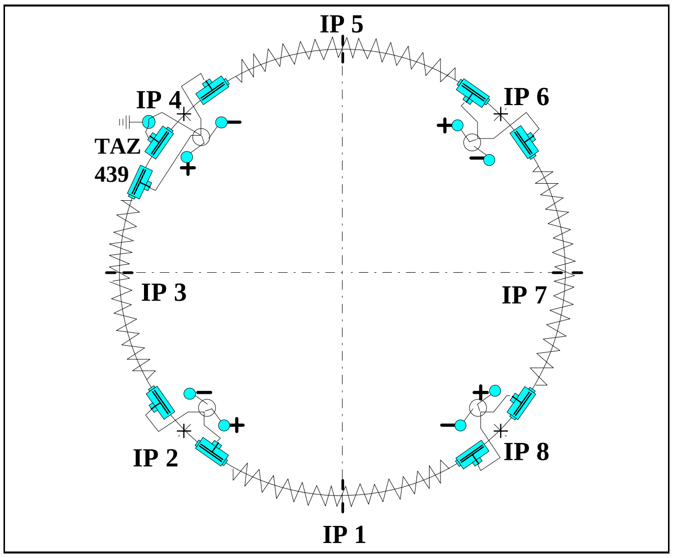

Figure 1: Schematic layout of the horizontal electrostatic separators for the pretzel scheme as it was in 1992. Local vertical separation bumps are used at the 8 IPs.

A. Injection and Intensity Limits

While filling LEP it is important to keep the individual bunch intensities, I_b, approximately equal. This is all the more true with pretzels when different values of I_b can generate different long-range beam-beam kicks, resulting in each bunch having its own closed orbit, tune and tune-spread depending on the sequence of beam-beam kicks it experiences. Unequal intensities also generate a richer spectrum of coherent beam-beam modes and extremely complex dynamic behaviour can result.

It was possible to fill all 16 bunches automatically: the 4 "normal" bunches on one SPS supercycle were followed by 4 interleaved bunches (displaced by $C/8$) on the subsequent SPS supercycle. However, for technical reasons, the bunch current equalisation system (used regularly

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with $k_b = 4$) could only act on 4 bunches of each beam. This forced us to adopt tricky strategies, filling one set of bunches at a time, which become increasingly difficult near the intensity limit where the lifetime is reduced.

To identify the source of the intensity limits at injection, several tests were done with the separators at 79 kV across 12 cm, giving pretzel amplitudes in mid-arc of about 9 mm. With a single beam (e^+ or e^-), 8 bunches of $I_b \gtrsim 500\,\mu$A could be accumulated. With two beams of 4 bunches crossing at the IPs (other conditions kept identical), the limit was around $I_b \simeq 450\,\mu$A. Both of these are similar to the limits without pretzel orbits. However when 4 electron bunches were injected against 4 positron bunches, displaced in time so that encounters occurred in mid-arc, the single bunch current limit fell to $I_b \simeq 300\,\mu$A. Although there has been no opportunity for detailed study, the limiting mechanism appears to be the coupling of the $m = 0$ and $m = -1$ head-tail modes, as it is with $k_b = 4$, but occurring sooner because of the mid-arc beam-beam encounters acting rather like an additional impedance.

For most of the operational period the separator voltage was set to 90 kV at injection, raising this limit to $325\,\mu$A. Going higher could lead to beam loss, probably due to the significant e^+e^- tune-split (typically of order 0.01) which could only be partially controlled with what was in effect a single sextupole family. In addition it was necessary to adjust the chromaticities as a function of pretzel amplitude to maintain head-tail stability.

B. *Transition to Physics Conditions*

Somewhat surprisingly, ramping and squeezing 16 bunches with pretzel orbits posed no particular problems with the low-emittance optics. Typically the separator voltage was ramped linearly from 90 to 120 kV while the beam energy changed from 20 to 45.6 GeV. However the beams were very sensitive going into collision, and time had to be spent carefully correcting (e^+e^- average) orbits and tunes before colliding to get good lifetimes and background conditions in the experiments. During these adjustments the current would fall, and inequalities among bunches would have a chance to set in, before physics conditions were declared.

C. *Corrections to the Optics*

At both 20 and 45.6 GeV, it was necessary to measure and correct the phase advance errors through the arcs which would otherwise cause non-closure of the pretzels (JMJ in [5]). This was done using the multi-turn acquisition of the orbit, from which the phase errors could be deduced by harmonic analysis to an accuracy approaching 1°. Phase advance corrections inside each pretzel were applied by scaling a pre-matched set of quadrupoles around the odd-numbered IP and produced exactly the intended effect. Compensating phase adjustments to keep the tune constant were applied in the low-β insertions, outside the pretzels. Typical errors were up to 12° in an quadrant. Direct correction of the β-functions was not attempted.

D. *Luminosity*

In tests at the end of a fill with $k_b = 4$, it was found that simply turning on the pretzel separators to 120 kV, would cause the measured luminosity to drop to 50–60 % of the level without pretzels. With $k_b = 8$, it was difficult to reduce the separators below this value without a loss of beam lifetime. Backgrounds in the experiments were perfectly acceptable.

Fine "Vernier" adjustment of the vertical beam separation at the IP, recovered some 15 % of this deficit. As explained above, only limited horizontal steering was possible (Figure 1) by varying the separator gaps. This was done around two IPs, recovering a further 10 % of the missing luminosity, but with the complications of inter-dependent settings. Finally the specific luminosity with pretzels was 75 % of that without. Non-symmetric settings around IP8 increased the luminosity. The vertical settings and the pretzel separator gaps were left at their optimum during the early physics runs.

Attempts were made to reduce the separator voltages during some pilot physics fills, but it was found that below 115 kV the experimental background rose.

A programme of detailed studies by experiment and simulation of parasitic beam-beam effects in combination with the head-on collisions was started with a view to understanding the energy-dependence of separation requirements for LEP2. In these experiments it was found possible to go to small or zero separation (for sufficiently low I_b) by careful adjustments of tunes, orbit and vertical separation. The results will be reported elsewhere [4].

E. *Electrostatic Separators*

The 8 electrostatic separators ZX are unipolar and operate at fields $\simeq 1\,\mathrm{MV\,m^{-1}}$ across gaps of 12 cm. In the test area TAZ (Figure 1), both separators have an insulated ground electrode for current and spark measurements. Without beam the spark rate of the separators is negligible, $< 10^{-4}\,\mathrm{h}^{-1}$. With beam, the synchrotron radiation from the main bends dramatically increases the spark rate for negative polarity; for positive polarity it remains acceptable (WK in [5]).

With positive polarity, no breakdowns were observed in the 7 standard separators in 1370 hours. Discharges were detected on the ground electrode of the special TAZ separator at normally distributed breakdown intervals of $1.9 \pm 0.1\,\mathrm{h}$. At 45.6 GeV some 30 % of events had a coincident HT signal indicating a discharge across the gap. These did not cause any beam loss or "background spikes" for the experiments.

With positive polarity sparks are only produced when the ground electrode is insulated. We therefore believe that the the screening effect of the positive electrode precents the HT insulators from being charged by photoelectrons produced by synchrotron radiation. An insulator at the ground electrode can, however, be charged, and subsequent de-trapping of these charges may trigger breakdown. For negative polarity the photoelectrons can charge the HT insulators, leading to breakdown.

Bunches per beam, k_b	8	4	Units
Average I at 20 GeV	4.8	3.0	mA
Best I at 20 GeV	5.6	3.8	mA
Average I into physics	4.5	3.0	mA
Best I into physics	4.8	3.5	mA
Average peak L	9	8	$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Best peak L	11.5	10	$10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Typical ξ_y	.025	.035	
Best ξ_y	.028	.0375	
$\langle L\rangle$ over fill	21	20	$\mathrm{nb}^{-1}\mathrm{h}^{-1}$
Best for fills > 6 hours	32	27	$\mathrm{nb}^{-1}\mathrm{h}^{-1}$
Fraction of fills lost	9 %	40 %	

Table 1: Comparison of performance achieved with the pretzel scheme in its operation so far (32 fills) and that achieved in the last 141 fills with $k_b = 4$; "Average" means average over the fills; I, the sum of the currents in both beams, is quoted at injection energy (20 GeV) and after ramping and "squeezing" to physics conditions with $\beta_y^* = 5\,\mathrm{cm}$; $\langle L\rangle$ denotes the average luminosity over a fill.

F. Performance Summary

Table 1 compares average and peak performances between $k_b = 8$ and $k_b = 4$.

Although the total current brought into physics conditions has increased by 50 %, the 25 % drop in the attainable beam-beam tune shift results in only a 10 % in luminosity.

The number of fills lost fell dramatically in comparison to $k_b = 4$ operation. Of the 3 lost only 1 was for unknown reasons. With $k_b = 4$, about half of the losses were never explained. The difference may arise from the value of I_b.

II. Polarization with Pretzel

One of the main reasons for choosing a purely *horizontal* pretzel separation for LEP was so as not to exclude the possibility of polarized beams. While it is clear that a vertical or helical separation scheme would depolarize strongly and that a *perfect* horizontal scheme would not, it was difficult to demonstrate that residual coupling would not be enough to depolarize the beam. Accordingly an experimental test was made on a pretzel optics with $\mu_x = 90°, \mu_y = 60°$, with the results shown in Figure 2. (It had not been possible to obtain polarization on the regular 1992 optics.)

Although a discrepancy remains between prediction and measurement of the energy shift due to the pretzel (JMJ in [5]), this result opens up the possibility of energy calibration by resonant depolarization in conditions as close as possible to those of physics data-taking and should help to improve the precision of measurement of the Z-boson mass and width.

III. Conclusions

After its successful start, the pretzel scheme must now go on to increase the luminosity of LEP.

At 20 GeV it is important to overcome the current limitation. An increased separation should be feasible with a new set of achromatic sextupoles which will provide complete control of the the e^+e^- tune-split. A comprehensive bunch equalisation system is a necessity.

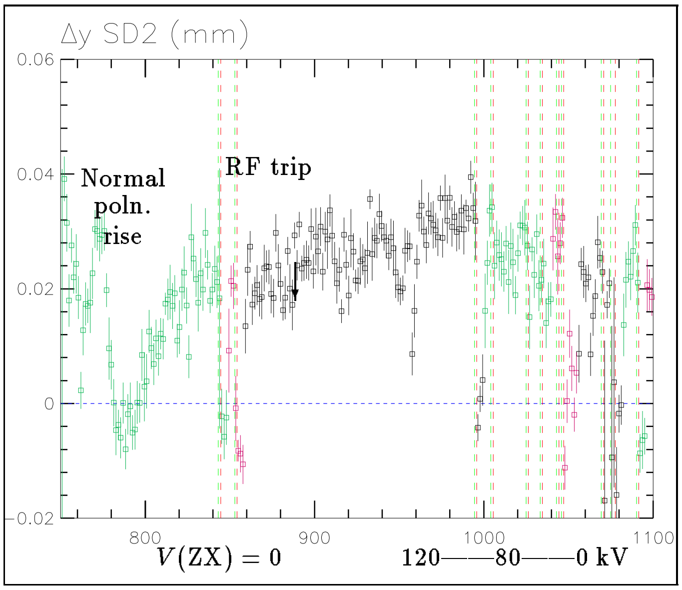

Figure 2: Transverse polarization, P, as pretzel orbits were switched on and then off again, following an period in which the polarization was allowed to rise normally with flat orbits. An asymmetry $\Delta y = 0.05\,\mathrm{mm}$ corresponds to a polarization level of 10 %. Resonant depolarizations (indicated by pairs of vertical dashed lines) were performed during a period of some 15–20 min, at the end of the experiment, in which the pretzel separator voltage was reduced from its maximum back to zero.

With higher currents, the requirements for control of the tunes and chromaticities (to keep both $m = 0$ and $m = 1$ head-tail modes stable) become more stringent.

Additional separators and sextupoles will facilitate correction of the defects of the machine. Reducing the separator fields in physics under carefully controlled conditions will help to reduce the effects of pretzel orbits.

Acknowledgements Many of our colleagues in CERN made valuable contributions to the commissioning of the pretzel scheme.

IV. References

[1] J.M. Jowett, "More bunches in LEP", Proc. 1989 IEEE Particle Accelerator Conf., Chicago, (1989) 1806.

[2] "Report of the Working Group on High Luminosities at LEP", E. Blucher, J.M. Jowett, F. Merritt, G. Mikenberg, J. Panman, F. Renard, D. Treille (Eds.), CERN Report, 91-02 (1991).

[3] W. Kalbreier *et al*, "The Pretzel Separation Scheme in LEP", Proc. XVth Internat. Conf. on High-Energy Accelerators, Int. J. Mod. Phys. A (Proc. Suppl.) 2A (1993) 401.

[4] J.M. Jowett, W. Herr, to be published.

[5] J. Poole (Ed.), Proc. 3rd Workshop on LEP Performance, CERN SL/93-19 (DI), Chamonix, 1993.