

## THE PRETZEL SEPARATION SCHEME IN LEP

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## Abstract

By means of a "pretzel" scheme to separate the beams in LEP, we plan to double the number of  $e^+$  and  $e^-$  bunches in the course of this year and so increase the luminosity at the  $Z^0$  production energy. Such a gain will be even more important from 1994 onwards at energies beyond the  $W$ -pair production threshold. Then we shall exploit the interplay between pretzel separation and the natural energy-sawtooth of the orbits. The eight electrostatic separators needed were available by the beginning of 1992. Only four of them were installed in 1991 but it was nevertheless possible to study pretzel orbits, beam-dynamics, beam-induced sparking of the separators and other aspects of the scheme using a special optics. Further hardware, including additional sextupoles, will be installed later. The separator spark rate was reduced to an acceptable level by an empirical method. We review highlights of the studies to date, the transition to physics operation and the issues determining future adaptations of the optics and hardware of LEP.

## 1 Introduction

The "pretzel" scheme to increase the number of bunches which can be collided in LEP has been under study for some 4 years now [1]–[5]. It was initially seen as a long-term option for turning LEP into a  $Z^0$ -factory with up to 36 bunches per beam. At the end of 1990, a wind-fall of electrostatic separators (known as 'ZX') recuperated from the Sp $\bar{p}$ S gave rise to plans to introduce such a scheme as quickly—and as cheaply—as possible. To avoid more extensive upgrades of several LEP systems [2], the more limited goal of providing 8 bunches per beam was set. Besides the possibility of increased luminosity at the  $Z^0$ , this nevertheless held out the prospect of increased luminosity above the  $W$ -pair production threshold after the energy upgrade of LEP.

During 1991, half of the necessary 8 ZX units were installed in and allowed a series of feasibility studies [4, 5]. This year all the separators are in place and a new low-emittance optics, designed for the pretzel scheme, is being used as the standard optics in *all* LEP operation.

## 2 Experiments with high-emittance optics

The pretzel experimental programme in 1991 [4, 5] was based on the separator configuration shown in Figure 1, allowing pretzel orbits in 2 quadrants of the ring.

## 2.1 Beam dynamics and optics

The pretzel scheme has always been intended for use with a low-emittance LEP optics ( $90^\circ$  of betatron phase advance per arc cell). At the beginning of 1991, all successful operation of LEP had been with a high-emittance optics ( $60^\circ$  per cell). Given the limited time available, these studies were based on a  $60^\circ$  optics as close as possible to the operational one. To satisfy the pretzel closure constraints the so-called HIBL insertions around the odd-numbered IPs were rematched but the experimental straight sections were left alone (as in all other LEP optics considered up till this year). Although unusual in being the only LEP optics ever to have betatron tunes  $Q = (Q_x, Q_y) \simeq (69.7, 75.6)$  in the upper half-integer, the optics was otherwise rather similar to the operational one.

The results of experiments on beam dynamics and optics are given in more detail in [4, 5]. The main difficulty was found to lie in obtaining an acceptable injection efficiency on pretzel orbits, with or without long-range beam-beam interactions in mid-arc.

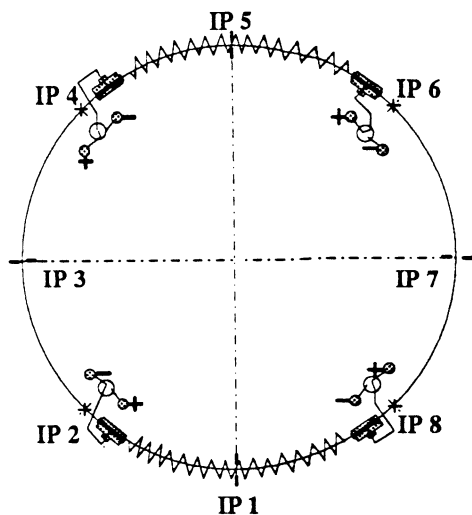
Beyond a threshold of 7–8 mm separation, corresponding to about  $5.5\sigma_x$  for the weak bunch, it was possible to accumulate an  $e^+$  bunch of  $100\ \mu\text{A}$  against a single  $e^-$  bunch of  $190\ \mu\text{A}$ . However injection rates were of the order of  $4\ \mu\text{A}/\text{min}$  even with 20 % more separation. Significantly larger separations led to poor lifetime and/or considerable difficulty in injecting a single beam. These observations can be attributed to the relatively large beam size and the dynamic or physical aperture of the  $60^\circ$  lattices.

Beams were ramped on constant amplitude pretzel orbits without losses. Emittance measurements confirmed the reduction in horizontal damping partition number with pretzel amplitude [5].

## 2.2 Separator studies

The electrostatic separators are unipolar, i.e., one electrode is connected to high voltage and the other to ground. Originally they were designed for operation in the Sp $\bar{p}$ S with negative polarity only. Many experiments were carried out with the parameters of Fig. 1. In particular, when the separators were operated with the negative design polarity, an unacceptably high spark rate in the presence of beam was observed. It was found empirically that this might almost be cured by operating the separators with positive polarity.





beam energy	46 GeV
electrode length	3.0 m
nominal electrode gap	120 mm
nominal field strength	1.5 MV/m
beam size at mid-arc, $\sigma_x$	2.66 mm
total separation	16.9 mm = $6.37\sigma_x$
vacuum pressure	$< 10^{-10}$ Torr

Figure 1: The half pretzel scheme in 1991 and typical parameters used with the high-emittance optics.

Without beam the spark rate of the separators is sufficiently small, i.e.,  $< 10^{-4}$  per hour. With beam and *negative polarity* they increase dramatically, whereas for *positive polarity* it seems that they remain low enough. For negative polarity there is a clear correlation between the increase in the spark rate and the presence of synchrotron radiation, depending on its origin. There are two sources of radiation which might affect the separators: (i) The more important is the main dipole magnets of the arcs; the flux of  $\geq 1$  keV photons incident on the outer electrode of a pretzel separator is as high as  $5 \cdot 10^{14}$  photons  $s^{-1}m^{-1}$  per mA of beam current. The critical energy is 69.4 keV. (ii) The other source, which is more difficult to estimate, is the quadrupoles in the experimental insertions; this flux is much lower but the critical energy may be higher depending on the  $e^+e^-$  trajectories in the quadrupoles.

For source (i) and negative polarity a strong increase in the spark rate, at nominal field by a factor of about  $10^4$ , was found. For source (ii) the increase is much smaller and estimated as  $< 10^3$ . The large difference in rates induced by synchrotron radiation from the two sources rules out the possibility that higher order mode losses might be the origin of the beam-induced sparking.

At 46 GeV with *negative separator polarity*, detailed study of the correlation between the spark rate and synchrotron radiation from dipoles has shown:

- At fixed field the spark rate is rather independent of the electrode gap and of whether the direct photons hit the HV electrode or the grounded electrode. The spark rate per ZX at the nominal field strength is  $3.6 \pm 0.6 h^{-1}mA^{-1}$ .
- The direct high energy photon flux incident on the separator electrodes is *not the main source* of sparks.

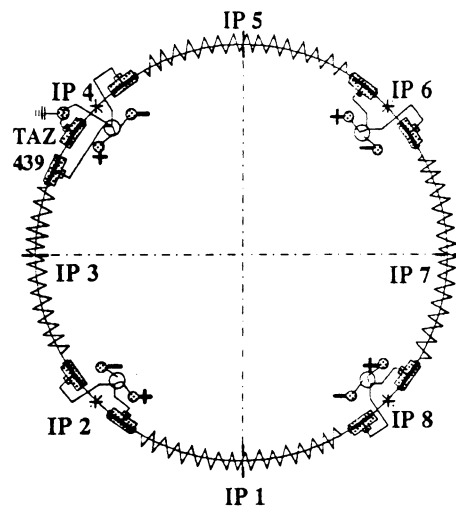


Figure 2: The full pretzel scheme including the TAZ in 1992.

This was verified by a scan with a horizontal collimator. The photo-current produced by synchrotron radiation photons hitting the electrodes is reduced by a factor 15 when the collimator is closed to protect the electrodes. Yet the spark rate goes down only by a factor  $1.5 \pm 0.5$ . Therefore low energy photons and electrons produced by the photo-effect appear to play an important role.

Subsequently, a similar study at 46 GeV with *positive separator polarity*, showed that, with open collimator, no sparks were observed in the same separator during a period of 3 hours at a field of 2.5 MV/m (58%) and 3.0 MV/m (32%). In these conditions, the spark rate with negative polarity would have been  $67 \pm 8 h^{-1}mA^{-1}$ .

### 3 Experiments with low-emittance optics

This year, all 8 ZX are available (Fig. 2). Furthermore a test area (TAZ)—consisting of a ninth ZX unit together with collimators, particle traps and improved spark diagnostics—has been installed to investigate the mechanism leading to beam-induced breakdown [5].

Most LEP operation in 1992 has been based on a new  $90^\circ$  optics designed to satisfy not only the phase advance and anti-symmetry constraints of the pretzel scheme [2] but also all other requirements on tunes and phase advances which are now known to be important for LEP. Although this placed more constraints on the matching than had ever been considered before, a solution was found with global tunes  $Q \simeq (94.3, 100.2)$  favourable for the beam-beam effect and polarization. It was necessary, for the first time, to substantially rematch the optics of the low- $\beta$  and RF insertions.

In the 9 hours of beam time obtained for pretzel studies so far this year, we were able to rapidly accumulate

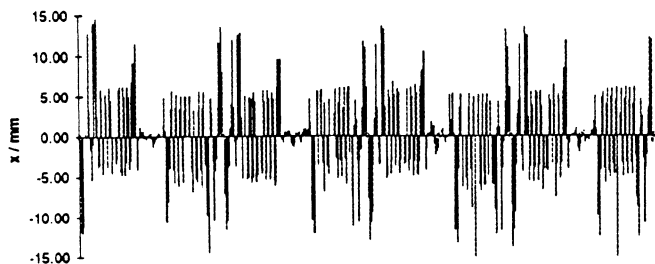


Figure 3: Horizontal  $e^+e^-$  difference orbit at 45.6 GeV with  $\beta_y^* = 5$  cm (after fit for pickup calibration/offset).

(rates up to  $200 \mu\text{A}/\text{min}$ ) 4  $e^+$  against 8  $e^-$  bunches. Injection was deliberately limited at  $200 \mu\text{A}$  per bunch. Injection bumps were set to slightly over-compensate the calculated  $e^+e^-$  pretzels. The pretzel bumps were very well closed at 20 and 45.6 GeV (Fig. 3).

In this configuration, 4  $e^-$  bunches have encounters at 8 IPs, the other 4 have encounters at 8 mid-arc points, and the 4  $e^+$  bunches have encounters at 8 IPs and 8 mid-arc points as in the full scheme.

The minimum separation for good lifetime at 20 GeV was about 16 mm between bunch cores at mid-arc encounters. At the mid-arc encounters this could be anything between about 5 and  $8.5\sigma_x$ . (The natural horizontal emittance being just 1.5 nm, the beam size is dominated by the energy spread which is blown-up by wigglers or instabilities).

These beams were then ramped, squeezed to nominal  $\beta_y^* = 5$  cm and collided with no losses (except some positrons at the start of the ramp, probably due to collimators). Although no attempt was made to maximise luminosity, the beam lifetime remained long (20–40 h) and no particular problem with backgrounds was seen. The increase of horizontal emittance on the pretzel before excitation of the emittance wigglers (measured  $\epsilon_x \simeq 20$  nm) was more than expected from calculation of  $J_x$  reduction ( $\epsilon_x \simeq 14$  nm). However the vertical emittances remained small, at  $\epsilon_{yc} \simeq 1\text{--}2$  nm.

The residual separation outside the pretzel bumps generally led to an almost anti-symmetric orbit around each IP with mis-crossings of the order of  $1\sigma_x^*$ . This will have to be improved by shunting betatron phase in and out of the pretzel regions. Residual vertical separation can be removed electrostatically.

The measured separator rates spark are compatible with the data obtained in 1991. In 3 hours at 46 GeV with positive polarity and a field strength of 1.3 MV/m a single spark was recorded without causing any beam loss.

#### 4 Conclusions and outlook

The first attempts to collide beams with pretzel orbits have demonstrated the advantages of the new low-emittance optics and it is likely that the pretzel scheme

will become the standard mode of operation both for the present  $Z^0$ -physics and LEP2.

The ZX separators must be operated at *positive polarity*. Then, an extrapolation to the nominal field of 1.5 MV/m results in a period without sparks of about 46 hours per ZX with a single beam current of 1 mA. For a full pretzel scheme with 0.5 mA per bunch this corresponds to  $\geq 1.4$  hours without sparks. Such a period without sparks is necessary because, even when the beam is not lost, the induced background spike might cause a detector trip. (With the original negative polarity in the same beam conditions, the period between two sparks would be just 2 minutes.)

Operation with positive polarity requires changes to the HV design of some components of the separators. More significant data on sparking will be obtained with the new test facility TAZ and from pretzel runs preparing the transition to physics operation.

At high energies in LEP, the  $e^+e^-$  orbits are separated by the “energy-sawtoothing” arising from the large radiation loss (1.9 GeV per turn at 90 GeV) and the localisation of the RF cavities. At 90 GeV this separation is about 3 mm at the mid-arc points. The signs of the electric fields in the separators are chosen [3] so that, with similar RF voltages installed around each of the 4 IPs, the pretzel separation will *add* to this effect at every mid-arc encounter. Thus, energy-sawtoothing will be exploited as an aid to the pretzel separation.

The strength of the present ZX separators is nevertheless marginal for adequate beam separation at the higher energies of LEP2. Studies on the energy and beam size dependence of the minimum separation will clarify whether new separators will need to be installed.

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