# MULTIBUNCH OPERATION OF CESR[*]

R. Littauer (*for the CESR Operations Group*[#])
Newman Laboratory of Nuclear Studies, Cornell University
Ithaca, New York 14853

## 1. Introduction

The Cornell storage ring CESR, designed to collide one bunch of $e^+$ with one bunch of $e^-$ at energies up to 8 GeV each, is used almost exclusively for research on b-quark physics (the $\Upsilon$ region, 4.5 - 5.6 GeV per beam). Here the radiation loss is less than one-quarter the design maximum--low enough to relax beam-current limitations due to total rf power, yet still high enough to provide a comfortable amount of radiation damping ($\tau_{rad} \approx 22$ ms), which helps control beam instabilities. Performance is therefore relatively good. With single bunches, the luminosity (which scales roughly as $E^4$) reaches about $1.6 \times 10^{31} cm^{-2}s^{-1}$ at 5.4 GeV. This is achieved with bunch currents of about 17 mA, in a regime where vertical beam blowup due to the beam-beam interaction makes $L \approx I$ rather than $I^2$. The beam current is limited to this level by the onset of sudden beam losses during collision.

To raise the luminosity, CESR has since 1983 operated with multiple bunches in each beam. At the unwanted crossing points within the guide-field arcs, these bunches are separated in the horizontal plane: $e^+$ and $e^-$ orbits are oppositely distorted, "pretzel" fashion, by a pair of electrostatic separators near the ends of each arc (Fig.1). The orbits still coincide around the two interaction points, and must do so very accurately of course. The required modifications of CESR, and early experience with multibunch operation, were described previously [1].

We report our progress here, as an example of the considerations applying when two beams are bedded side-by-side in the same aperture, separated by electrostatic steering elements. The topics are: design constraints, Sec.2; lattice-optical and orbit effects, Secs. 3 and 4; and beam performance, Secs. 5 and 6.

Table 1

*Some CESR Parameters*
*(Typical Luminosity Lattice, 5.4 GeV)*

| | |
|---|---|
| Revolution frequency | $f_0$ = 390 kHz |
| Magnetic bending radius | $\rho$ = 88 m / 32 m |
| Chamber aperture | $A_x$, $A_z$ = ±45, ±25 mm |
| Betatron tunes | $Q_x$, $Q_z$ = 9.394, 9.371 |
| β function (typ, in arcs) | $\beta \approx$ 8 - 35 m |
| Dispersion function (typ) | $\eta \approx \leq$ 3 m |
| Horizontal betatron emittance | $\varepsilon_x = 1.6 \times 10^{-7}$ m |
| Momentum compaction factor | $\alpha_p$ = 0.015 |
| Radiation loss | $U_0$ = 1.12 MeV/turn |
| Momentum spread | $\sigma_p/p = 5.8 \times 10^{-4}$ |
| *At Interaction Points (S/N):* | $\beta^*_x$ = 0.9 / 1.0 m |
| | $\beta^*_z$ = 3.25 / 3.0 cm |
| [G99327.9A7] | $\eta^*$ = 0.78 / 0.70 m |

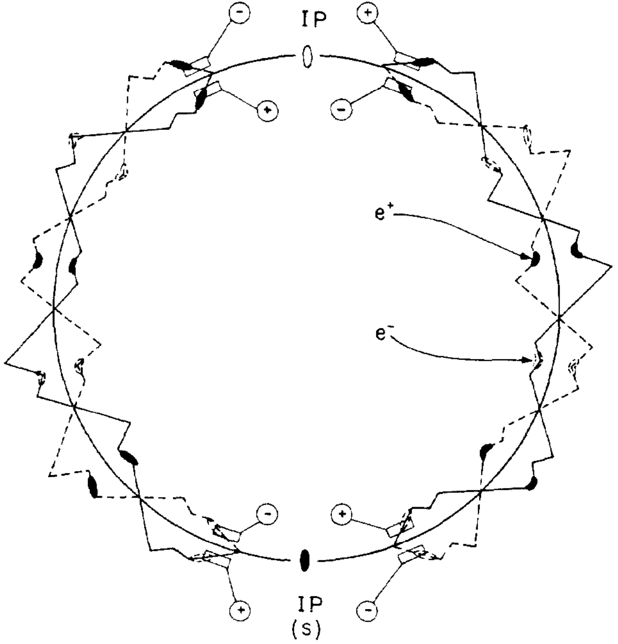

*Fig.1: $e^+$ and $e^-$ orbits in guide-field arcs of CESR (not to scale). Encounter points for 7 × 7 bunches, at one time, shown in black; bunches also meet at locations shown dotted.*

## 2. Basic Design Considerations

Pretzel closure [2]: The lattice is constrained (by adjustment of individual quadrupole gradients) to produce exactly $6\pi$ horizontal betatron phase advance between the separators at the ends of each pretzel. This closure condition is trimmed, operationally, by trading quadrupole gradient within the pretzel for quadrupoles outside, keeping the tune of the machine constant. At the same time, the ratio of separator deflection angles is trimmed as needed. Figure 2 illustrates the degree of closure obtained under optimum conditions, measured as the orbit displacement produced by turning on and off a pretzel in just one of the two arcs [3]. Residual errors outside the pretzel region are well below 0.1 mm, which is small compared to the horizontal beam dimensions (typically, $\sigma_x$ = 2 - 3 mm).

Pretzel symmetry: We have tried symmetric and antisymmetric pretzels in the two arcs, ending with a slight preference for the antisymmetric pattern (as shown in Fig.1). This eliminates, to first order, tune differences between the two beams and lateral separation at collision, which occurs at the symmetry points. It leaves open the possibility of angular errors between the beams at crossing, and breaking of the two-fold superperiod for each beam, as regards betatron phase shift from one crossing to the other [4].

Orbit isochrony: A deflection $\theta$ at a point where the dispersion function is $\eta$ produces an orbit elongation of $\eta\theta$. Thus the pretzel leaves the orbit length unchanged, and does not perturb the particle's synchrotron phase, if $\eta_1\theta_1 + \eta_2\theta_2 = 0$, for the two deflections at the ends of the pretzel. Since for closure we require $\theta_1\sqrt{\beta_1} + \theta_2\sqrt{\beta_2} = 0$, we constrain the lattice to yield

$$\eta_1/\sqrt{\beta_1} = \eta_2/\sqrt{\beta_2}$$

In addition, *anti*symmetric pretzels leave the orbits isochronous, overall, even without this constraint.

---

[*] Work supported by the National Science Foundation.

[#] M.Billing, E.Blum, D.Dean, G.Decker, M.Giannella, S.Herb, G.Jackson, R.Littauer, B.McDaniel, D.Morse, S.Peck, S.Peggs, D.Rice, G.Rouse, D.Rubin, L.Sakazaki, R.Siemann, R.Talman.

0018-9499/85/1000-1610$01.00© 1985 IEEE

Pretzel utilization: This can be gauged by how nearly the factor $\sin\mu_n$ approaches unity, where $\mu_n$ is the horizontal betatron phase advance from a separator to the $n^{th}$ point of (separated) bunch encounter in the arcs. We typically achieve a utilization of at least 0.9, i.e., the minimum bunch-bunch separation is 90% of the maximum it could reach, relative to the local beam dimension $\sigma_x$. An impression of this, for the case of 7 × 7 bunches, is conveyed by Fig.1; because our rf numerology does not permit equal spacing of 7 bunches, the bunches are there shown lengthened to represent the ±1.8-m variation in the actual bunch encounter point, depending on the particular pair of bunches involved. (For 3 × 3 bunches we have equal spacing. The lattice can be optimized separately for 3- and for 7-bunch operation, if desired.)

## 3. Sextupole Patterns

Most storage rings are operated at slightly positive chromaticity $\xi = (p/Q)(dQ/dp)$, obtained by suitably distributed sextupoles. There are usually at least two "families" of sextupoles: those near points of maximum $\beta_x$, and those near maximum $\beta_z$. This permits control of chromaticity in both planes. In the presence of pretzels, these sextupoles now become the subject of particular concern, because the separated orbits pass far off-center through many of them. This leads to distortions of the lattice functions which may affect the two beams differentially. Overall, sextupole effects play a dominant role in the pretzel scheme--second only to worry about the availability of sufficient aperture to accommodate the beams physically.

Off-center passage of the closed orbit through a sextupole introduces a quadrupole term. For a horizontal offset this represents a normal quadrupole, modifying the focusing and consequently the β function. A vertical offset produces a skew-quadrupole term that adds x-z coupling. (Vertical offsets may occur through orbit misalignment, but also differentially between the beams due to pretzel imperfections; see below.)

We require that the betatron phase advances through the pretzels remain equal for the two beams, in both planes. To achieve this, sextupole strengths may be modified within the pretzels appropriately, but these changes must not disturb the desired chromaticity in either plane. Altogether this calls for four degrees of freedom, i.e., for four families of sextupoles within the pretzel.

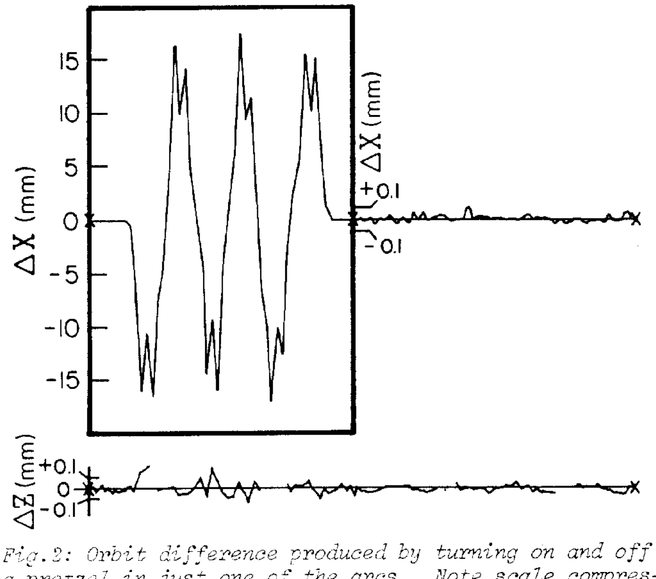

*Fig.2: Orbit difference produced by turning on and off a pretzel in just one of the arcs. Note scale compression by a factor of 10 within the pretzel region.*

Beyond changing the betatron phase advance, modification of the β function for a displaced orbit effectively mismatches the lattice, launching a β wave that perturbs the whole ring. Depending on lattice details, this change of β may be especially irksome near the interaction points. By use of further degrees of freedom in the sextupole pattern, β and β' can be correctly matched at the ends of the pretzel.

With 37 sextupoles within each pretzel, there is ample freedom in principle for adjusting their excitations so as to meet many requirements. However, in some of the resulting patterns, individual sextupoles may be assigned uncomfortably high strengths, giving rise to concern about the resulting limitation of dynamic aperture. Our design optimizations have been weighted toward minimizing peak sextupole excitation [5]. Operating experience indicates that, in a lattice where the β wave is uncomfortable, it pays to use a pattern which reduces this wave. Beyond this observation, no significant effects attributable to sextupole pattern have so far been identified.

## 4. Some Further Details

Vertical orbit differences: Any coupling element at a point of horizontal orbit separation introduces an incidental *vertical* orbit difference which can propagate to the interaction points, misaligning the bunches at collision. For example, when the orbit passes through a sextupole above or below the median plane, a skew-quadrupole component is encountered. Skew quadrupoles also result from inadvertent tilt of the guide-field quadrupoles. In either case, a (deliberate) horizontal offset then translates into a vertical deflection. (Vertical orbit separation can also be caused by accidental tilt of the separators themselves.)

We compensate for vertical orbit separation by empirical adjustment of two skew-quadrupole correction elements within each pretzel. Under optimum conditions, the vertical orbit "ripple" outside the pretzel region (Fig.2) is small enough, even relative to the small vertical beam size, to make further correction at the intersection points unnecessary. (We tried such a correction without obtaining any increased luminosity.)

Vertical ripple *within* the pretzel, even though compensated overall to cancel any orbit separation at crossing, can still induce vertical dispersion and vertical betatron emittance. Both these effects augment the vertical beam size at crossing. However, in comparing the luminosity degradation produced by two pretzels of different internal vertical ripple, we observed no correlation with this particular aspect.

Differential coupling parameters: The x-z coupling of the beams must usually be adjusted critically to obtain maximum luminosity. With separated orbits (involving, for example, accidental vertical displacements within the pretzels at the sextupoles), it is possible for the two beams to have different couplings. Not only might this influence the beam-beam interaction mechanism, but it might also leave the two beams colliding with elliptical cross sections tilted different ways so as to reduce their effective overlap. The use of *skew sextupoles* within the pretzels can correct such effects. So far we have worked with only one such skew sextupole per pretzel. These elements are adjusted to have both beams well decoupled simultaneously; from this initial setting, the operators occasionally find that small empirical changes can be helpful.

Injection: Injection is in the horizontal plane at CESR, impressing on the injected particles large oscillation amplitudes that subequently damp away. In the case of $e^-$ (which must be injected against a fully stacked $e^+$ beam), we then have the injected $e^-$ initially running the gauntlet of opposing bunches with inadequate separation. As a result injection becomes progressively harder as more numerous and more intense e$^+$ bunches are utilized. We have taken two steps to increase the effective bunch separation during injection:

(a) The e$^-$ beam (but not the e$^+$ beam) is subjected to a short magnetic deflection directly after injection, timed so as to reduce the injection amplitude and give a corresponding excitation to the stored e$^-$ beam instead. This redistribution of the unavoidable evil reduces the maximum oscillation amplitude to be carried by any e$^-$, stored or injected. The magnetic pulser is located off-center at a pretzel maximum and can thus influence the e$^-$ much more than the e$^+$.

(b) We add a component of *vertical* separation in the injection lattice, obtained (unavoidably!) from lack of closure of the vertical-separator orbit bumps in the two interaction regions. Those separators were forced away from their ideal 180° points by physical constraints when CESR was equipped with mini-beta insertions; now we capitalize on this result by arranging the lattice so as to place peaks of vertical beam separation near most of the bunch encounters in the arcs. Though this separation is small (typically ±3 mm), it helps very noticeably with injection.

In addition, a thinner injection septum has been built, which should further reduce the injection amplitude. This septum will be installed soon.

## 5. Performance

The orbit and lattice-optical aberrations produced by the pretzels can be brought under control, and we believe that we have gone a long way toward eliminating problems specifically associated with such errors. Instead, multibunch performance is limited by some more directly inherent features.

Horizontal-aperture requirements: We observe that beams in collision develop non-gaussian "tails" in their horizontal, as well as in their vertical, density profiles. The well known vertical blowup is what normally limits the beam currents and lowers the specific luminosity. The horizontal blowup is less dramatic, especially when expressed in terms of the much larger horizontal beam emittance; yet it proves to be a painful surtax on our already overstrained aperture. In the range from 8 - 16 mA, the tails grow by 1 - 2.5$\sigma_x$ (Fig.3). To provide clearance from the walls as well as between the tails of either beam and the center of the other, this adds 3 - 7.5$\sigma_x$ to the required aperture, which translates into 9 - 23 mm at points of maximum $\sigma_x$.

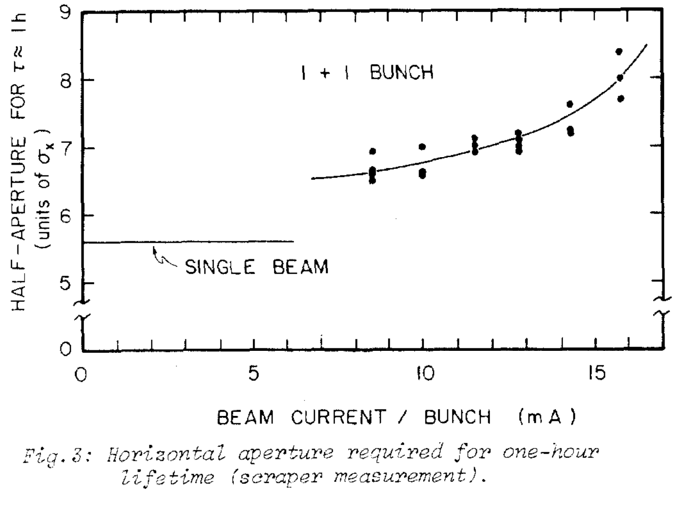

*Fig.3: Horizontal aperture required for one-hour lifetime (scraper measurement).*

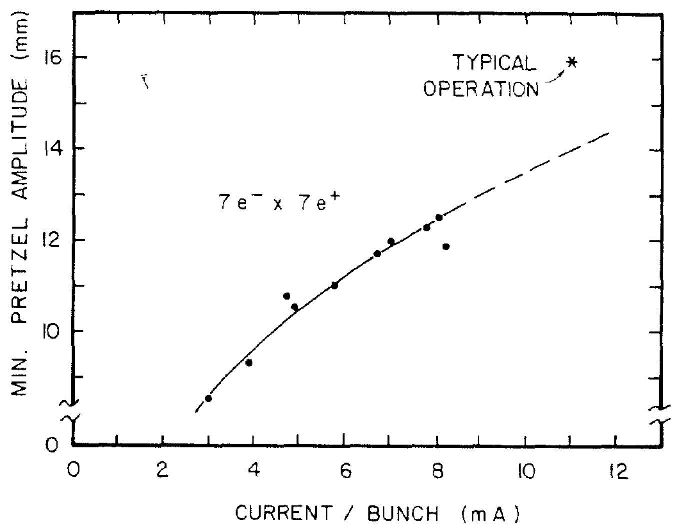

*Fig.4: Minimum pretzel amplitude for 7 × 7 bunches.*

Minimum pretzel amplitude: To accommodate the large-amplitude particles safely, the bunch separation at the encounters becomes so large that the beam-optical interaction at the *cores* of the bunches is quite small. The beam-beam dipole force produces orbit ripples of no more than about 0.5 mm. The quadrupole term, with 7 × 7 bunches of 10 mA each, gives a tune shift $\Delta Q_x \approx 4 \times 10^{-3}$, with $\Delta Q_z$ even smaller [1]. This tune shift is corrected when the operator optimizes conditions for luminosity.

We have no hard-and-fast data on the distance of minimum approach actually permissible between a particle in the *tail* of one bunch and the center of the opposing bunch. That depends on circumstances, particularly when the machine is tuned critically to cope with the beam-beam effect at the interaction points. However, there is a fairly definite minimum pretzel amplitude below which lifetime suffers (Fig.4). The pretzel amplitude for best luminosity is somewhat larger than this minimum.

Colliding-beam performance: Achieving maximum luminosity is something of an art, in most e$^+$-e$^-$ colliders, and CESR is no exception. This makes rigorous comparison of performance under various conditions difficult; normally there is not time to optimize the situation in all cases, and the condition most recently honed to fine perfection has an unfair advantage. However, our initial experiments with turning on the pretzels indicated a considerable luminosity degradation, leading us, in [1], to remark that "we find ourselves with a new machine on our hands." Progressive reduction of the various secondary effects discussed in Sections 3 and 4 has gradually improved the situation.

At present, turning on the pretzels tends to degrade the luminosity by no more than 10 - 15%, a level beyond which further progress becomes very tedious. Figure 5 illustrates this performance. The machine-studies data were taken with 1, 3, and 7 bunches per beam under otherwise similar conditions; the 1 × 1 physics run has no pretzels, of course. On the whole, luminosity *per bunch* is roughly independent of the number of bunches. However, the total luminosity achievable is limited in another way: the maximum bunch currents that can be used become progressively smaller. The lifetime under collision decreases much faster with current in the multibunch situation (Fig. 6). This decrease is not inconsistent with our known aperture budget, including the nongaussian tails.

Another, presently much more painful limitation arises from the side effects of the large total beam current. For a period of several weeks, CESR was operated regularly with 7 × 7 bunches, reaching *total* beam currents of 160 mA. The general vacuum accommodated to this load relatively easily. The rf cavity, on the other hand, showed dangerous heating of the ceramic input window, caused by the larger rf power requirement and by the higher-order mode losses induced by the beam. Ultimately, window cracking forced a retreat to 3 × 3 bunches. Work on an improved cavity window is under way.

Luminosity summary: The luminosities achieved during regular running, at each of the two interaction points, are as follows:

| | Peak | Integrated (one day) |
|---|---|---|
| 1 × 1: | $1.6\times10^{31}$ cm$^{-2}$s$^{-1}$ | 600 nb$^{-1}$ |
| 3 × 3: | $2.6\times10^{31}$ cm$^{-2}$s$^{-1}$ | 900 nb$^{-1}$ |
| 7 × 7: | $3.7\times10^{31}$ cm$^{-2}$s$^{-1}$ | 1400 nb$^{-1}$ |

The 3 × 3 performance, limited by lifetime degradation, probably represents the present machine's capabilities. The 7 × 7 luminosity was restricted by the rf cavity's total-current limit; there is good expectation that the peak luminosity may rise to around $4.5\times10^{31}$ cm$^{-2}$s$^{-1}$, once this restriction has been overcome.

Outlook: Beyond general improvements being planned (micro-beta interaction regions, injection directly into the luminosity lattice), specific ideas concerning the multibunch limitations are scarce. Horizontal aperture shortage appears to be the major problem. Short of reconstructing CESR entirely, this problem could be alleviated only if the horizontal beam size under colliding-beam conditions could be reduced.

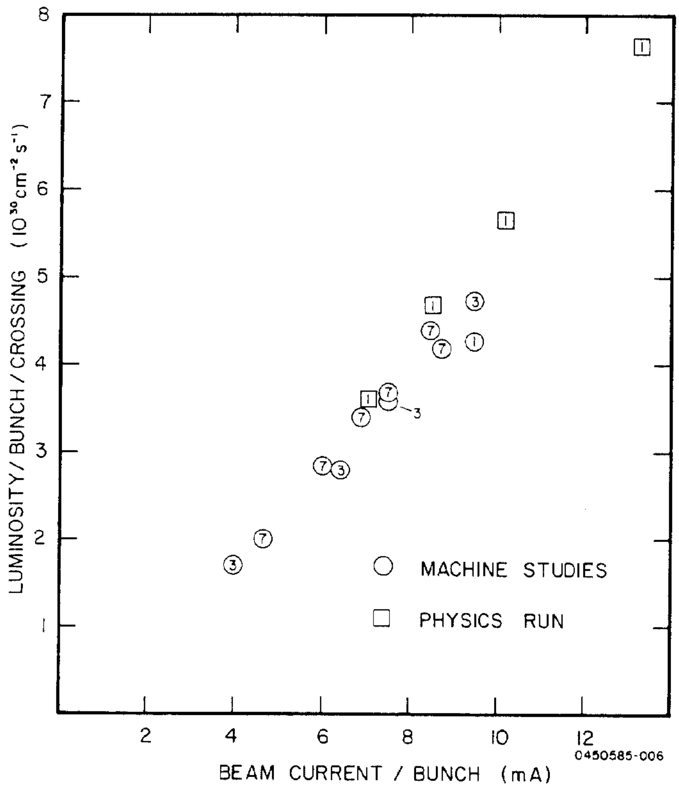

*Fig. 5: Luminosity* per bunch, *under similar conditions, for 1, 3, and 7 bunches per beam. For comparison, a 1 × 1 luminosity run (no pretzels).*

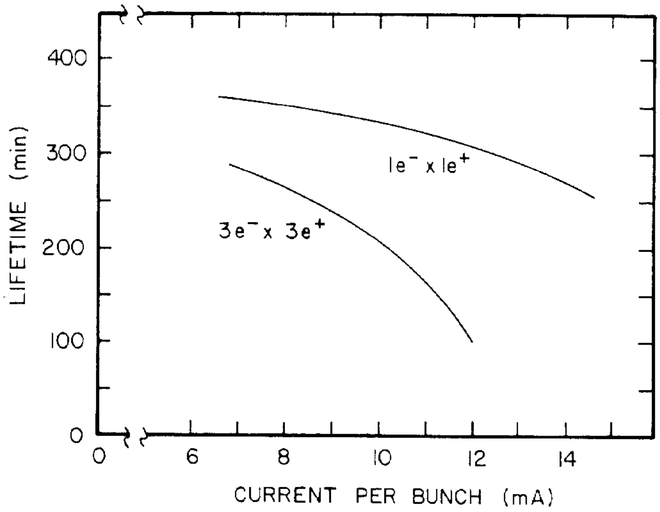

*Fig. 6: Lifetime degradation as function of current.*

## 6. Miscellaneous Problems

Multibunch instabilities: Such instabilities are observed, mainly for horizontal betatron oscillations, and have been studied extensively [6]. Fortunately they have presented no serious operational problems, since they do not occur after the beams are in collision and since up to that point they can be controlled by the use of positive chromaticity and narrowband transverse feedback.

Ion trapping: The separated e$^-$ beam can trap ions. This leads to reduced lifetime as well as to considerable modification of the beam's dynamic properties. Very occasionally, a CESR run does in fact revert suddenly into a short-lifetime condition, from which it can only rarely be rescued. (Single e$^-$ beams display ion trapping more regularly, but they can often be "shocked" back by some sudden, violent perturbation. Colliding beams are not so robust.) We have so far not studied the ion-trapping problem extensively.

## References

[1] R.Littauer, B.McDaniel, D.Morse, and D.Rice, Proc. 12th Int.Conf.on High-Energy Accelerators, 161 (1983).

[2] D.Rubin, CON85-5, Wilson Laboratory, Cornell Univ. (1985).

[3] Nulling the external orbit differences between pretzel-on and pretzel-off conditions does not, strictly speaking, null the e$^+$-e$^-$ orbit difference with the pretzel on, because of even-order terms in the expression for the pretzel ripple. See ref.[2].

[4] A.Piwinski, IEEE Trans.Nucl.Sc., Vol.NS-30, No.4, 2378 (1983).

[5] M.Billing, CBN84-10, Wilson Laboratory, Cornell Univ. (1984).

[6] L.Sakazaki, R.Littauer, R.Siemann, and R.Talman, "Anomalous, Nonlinearly Current-Dependent Damping in CESR," (this conference).