PROPOSED MULTIBUNCH OPERATION OF CESR*

R.Littauer, B.McDaniel, D.Morse, and D.Rice
Wilson Laboratory, Cornell University, Ithaca, NY 14853

Summary

CESR is an 8-GeV single-ring e^+-e^- collider with one pair of diametrically opposite interaction regions (IRs). It was designed to use a single bunch each of e^+ and e^-. Because of the rich physics interest in the T region (around 5 GeV beam energy), CESR normally operates well below its design maximum, with greatly reduced rf power requirements. The current that can be stored is however limited by the beam-beam interaction. To increase the total current and luminosity, it is attractive to consider multibunch operation. For this, destructive bunch encounters in the guide-field arcs must be avoided by separating the e^+ and e^- orbits at all crossing points other than the IRs. Such separation calls for additional aperture, but we believe this to be available in CESR.

We have modified the CESR ring for use with 3, 5, or 7 bunches in each beam and report here the details of the design and some preliminary observations made during early beam trials.

Project Outline

Present Operation

CESR currently operates with $\beta_z^* \simeq 3$ cm. At 5.3 GeV its linear tune-shift parameter ξ saturates at about 0.025, yielding luminosities somewhat above $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in each IR with bunches of about 2.5×10^{11} particles (16 mA; f_o = 390 kHz). At this intensity the bunches are blown up vertically and the luminosity is proportional to I, not I^2. We believe that maximum usable current is reached when non-gaussian "tails" on the vertical bunch profile fill the available chamber aperture.[1]

In the guide-field arcs the aperture is ±45 mm × ±25 mm. The β function has periodic maxima of about 35 m. With a horizontal emittance of 0.24 µm-rad and a dispersion of typically 2 m, the bunch profile ranges up to $\sigma_x \simeq 3$ mm in the arcs; depending on coupling and beam blowup, σ_z is considerably smaller.

Beam Separation at Arc Crossings

Separation of oppositely charged bunches is achieved by electrostatic separators.[2] Such separators, routinely used to avoid bunch collisions at the IRs during injection, are nontrivial structures, operated at very high voltages. Inserting them into the arcs of the accelerator requires considerable space. The separators also introduce significant impedances into the beam environment. Thus it is desirable to use as few separators as possible.

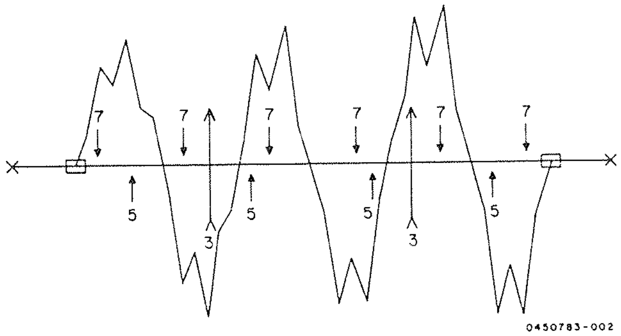

Figure 2

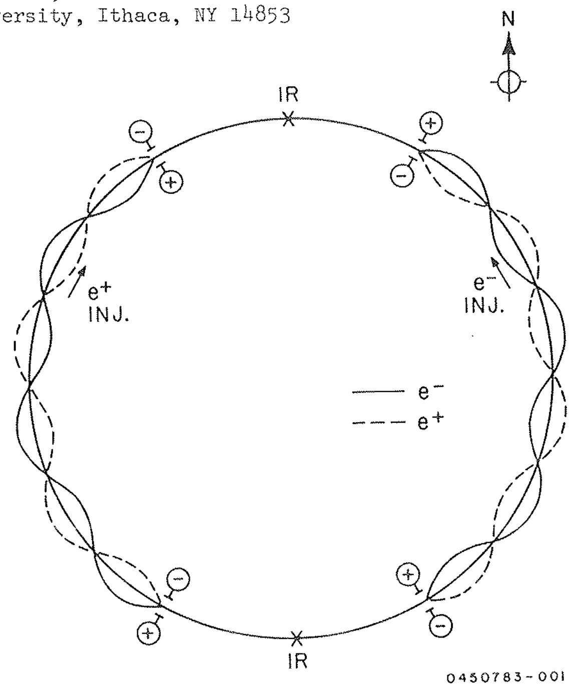

Figure 1

As shown in Fig.1, a single pair of separators spaced by exactly $n\lambda_\beta$ can be placed in each arc to produce $2n$ regions of large beam separation. We have nicknamed this type of orbit distortion a *pretzel*. CESR's lattice readily accommodates $n = 3$; the resulting pretzel (Fig.2) is consistent, after minor lattice adjustments, with 3, 5, or 7 bunches per beam.

For beam separations large compared to the bunch dimensions the bunch field can be represented as that of a thin line charge. This field has multipole terms of all orders. The dipole term produces a mutual beam deflection at the crossings which can in principle be compensated by lattice adjustments. The quadrupole term accounts for the familiar linear tune-shift parameter ξ. At a large distance D from a bunch of N particles,

$$\xi = \frac{\beta r_e N}{2\pi\gamma D^2}$$

in the usual notation. We do not know the maximum value of ξ which can be tolerated under various conditions; however, $D \simeq 10$ mm is enough to bring ξ down to 4×10^{-3} even at maximum β, so that the minimum clearance need not be very large. On the other hand, the center-to-center beam separation must be considerably larger than this minimum D if one wants to accommodate particles with oscillation amplitudes as large as 5σ or 6σ.

Vertical or Horizontal Separation?

It is customary to separate the beams vertically at the IRs during injection. This choice is appropriate for flat beams and where the separation is comparable to the bunch width, since it minimizes the field gradient. The situation in the arcs is different. Here, to allow for vertical beam blowup during colliding-beam operation, we must always work at separations large compared to the bunch dimensions, and the bunch field then depends chiefly on the distance D and not on the plane in which D lies.

Keeping the vertical beam size at the IRs small requires small vertical emittance and small vertical dispersion at the IR. Both these requirements would be jeopardized by the introduction of significant *vertical* orbit distortions into a large fraction of the machine's circumference. We have therefore chosen to separate the beams *horizontally* in our pretzels. There are several other considerations which favor this choice: (1) vertical orbit displacements in the lattice sextupoles would produce x-z (skew-quad) coupling, increasing the vertical emittance; (2) vertical aperture already appears to be at a premium for colliding beams at large currents; and (3) any residual e^+-e^- orbit misalignment produced at the IRs by the pretzels can probably be tolerated more readily in the horizontal plane, where the emittance is large anyway.

The Separators

Placement. A natural space for the south member of each pair exists in the CESR floorplan, in the straight sections adjacent to the rf cavities. (Unfortunately the cavities are *within* the pretzel region, but the beam separation there is not very large.) To accommodate the north separators, one guide-field dipole is removed and the adjacent dipoles are given 1.5 times as many excitation turns to replace the bend angle thus lost.

Structure. For horizontal separation we need vertical plate electrodes; these must have a gap in the median plane to permit harmless passage of synchrotron radiation. The electrode spacing is relatively large to match the horizontal aperture elsewhere. The design parameters of our separators are as follows: electrode spacing = 0.12 m, length = 2.54 m; beam deflection (5 GeV, ±100 kV) = 0.8 mrad. A photograph of the structure appears in Fig.3; there are water-cooled tapered traps for the synchrotron light at the ends of the enclosure. The electrodes are cooled by liquid Freon[3] which also bathes the atmospheric-pressure side of the insulators.

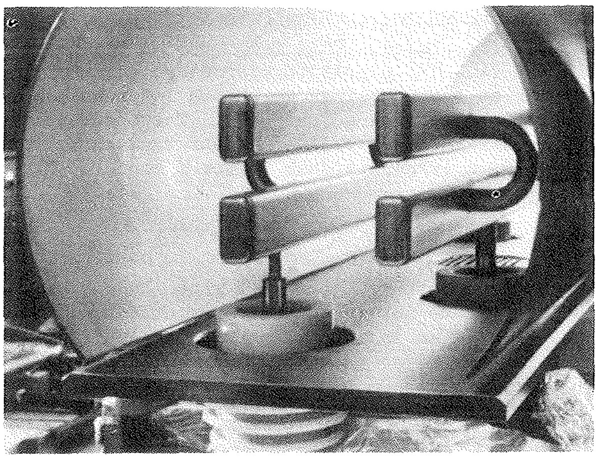

Figure 3

Model measurements of higher-order mode losses,[4] and estimates from the actual coolant temperature rise, put the longitudinal loss parameter at k = 0.27 V/pC for σ_s = 25 mm (similar to values achieved in our vertical separators). Introduction of four horizontal separators has not significantly changed the observed coherent transverse tune shift, dQ/dI.

The separators are powered by regulated high-frequency voltage multipliers[5] which are set to apply equal positive and negative voltages to the two electrodes. Present operation has extended up to ±130 kV, but there are still occasional discharge problems at this maximum voltage. At ±100 kV the pretzels have peak orbit displacements of ±14 mm and operation is fairly reliable. Further high-voltage processing (done in the presence of about 10^{-4} Torr of nitrogen) would probably extend the range to higher voltages.

Pretzel Adjustment

Closure. To ensure zero beam separation outside the pretzel regions--particularly at the IRs--we must adjust two parameters, the ratio of the deflections at the two separators and the horizontal betatron phase advance between them (in our case 6π). The CESR lattice has been modified to produce this phase advance nominally, with pretzel maxima near the crossing points for 3 or 7 bunches (Fig.2). To correct residual errors and to compensate for the beam-beam dipole deflections, we are prepared if necessary to insert a third (trim) separator into each pretzel; we hope to avoid this complication, however. The flexibility of the CESR lattice, with individual control of all elements, suggests that appropriate small corrections can be made by "massaging" the quadrupoles in the pretzel regions.

Tune Split. Horizontal orbit separation in a sextupole produces an e^+-e^- tune split. The algebraic sum of such splits in our 3λ pretzel is small: it can be made zero by minor changes in the sextupole excitations along the pretzel.

Dipole Effect. The mutual deflection of two beams of the usual intensity crossing at a separation of 20 mm (i.e., ±10 mm pretzels) is about 6 μrad, which produces a small but not negligible nonclosure of the pretzel. This effect can be corrected by adjusting the quadrupole near the crossing point and then restoring the phase advance in both planes by changing two other quadrupoles at which the beam separation is small. The calculated quadrupole changes are only a few parts in 10^3; we have not yet instrumented ourselves to measure the beam-beam deflection directly, nor experimented with the proposed correction.

Injection

Obviously at least one of the beams must be injected when the other has already been accumulated to full current. Since the injected particles make large horizontal oscillations, they risk approaching this opposing beam too closely, making them unstable and ruining injection.[6] We have indeed experienced this problem. To alleviate it we increase the beam separation and reduce the injection amplitude as much as possible.

At the injection septum the pretzel moves the beam being accumulated closer to the septum and the opposing beam further away. The permissible orbit displacements are not, however, the same, because the injection mechanism requires substantial clearance from the septum. For maximum separation between the two beams it is then desirable to displace them unequally from the center of the vacuum chamber. This is done by adding *magnetic* deflectors to the electrostatic separators.

The oscillation amplitude of a particle can be reduced after injection by giving it a suitable pulsed deflection. The bunch already accumulated, experiencing the same deflection, is of course excited to some extent. Overall, the clearance at closest approach to the opposing beam can be increased--provided, however, that the opposing beam is not simultaneously excited as well. Time or spatial separation at the pulsed deflector permits the opposing beam to be sheltered.

We have not yet developed these techniques very far. However, we can inject e^- at several mA/min against 3 bunches of e^+ of 15 mA each, a very encouraging initial level of performance.

Possible Multibunch Problems

Instabilities. Though we have experienced no clearly identified multibunch instabilities at our present levels of 3×3 bunches of 11 mA each, we must expect trouble as the number of bunches and the beam current are increased. Possibly this will call for the use of wideband feedback to stabilize the bunches individually.

RF Cavity Loading. The increase in total current imposes greater stress on the rf cavity, particularly in the form of higher-order mode losses (HOML). We are presently approaching some of these engineering limits. However, our cavity is known to have defective HOML loads; we hope to substitute another cavity which can be processed to a higher level.

Vacuum. Outgassing due to the more intense synchrotron light raises the residual pressure and shortens beam lifetime. Continuous operation will probably alleviate this problem, but we may be forced to bake the vacuum chamber--a chore so far avoided.

Separator Reliability. The pretzel scheme amounts to using electrostatic *guide-field elements* in the colliding-beam situation. This imposes severe stability requirements which will not be easy to satisfy.

Ion Capture. The e^- beam, separated from the e^+ which normally neutralizes it, can trap ions, which reduce beam lifetime and may produce instabilities. Ion trapping by intense e^- beams, stored alone, has been observed occasionally at CESR. However, we have no detailed information about the parameters involved and do not know under what conditions such an effect would arise with the pretzels.

Preliminary Results

For technical reasons all beam trials so far have been limited to 3 bunches per beam, at most. It is too early to make any definite statements about the ultimate prospects for our proposed new operating scheme for CESR. We have explored some of its aspects and obtained the following indications:

1. If the horizontal aperture is explored in single-bunch (1×1) colliding-beam operation by distorting the orbits of both beams together (i.e., using *magnetic* deflections), luminosity and lifetime are maintained up to peak pretzel amplitudes of ±16 mm.

2. Applying opposite pretzels to the orbits of the two bunches (i.e., using the *electrostatic* separators) is somewhat harder. Beam lifetime becomes more sensitive to tuning and the luminosity is reduced by about 20%. The mechanisms responsible for this increased difficulty have not yet been identified.

3. Pretzel amplitude needed to maintain good lifetime for a bunch encountering an opposing bunch *only* in the guidefield arcs is about ±12 mm for bunch currents of 15 mA.

4. When a bunch collides with another in the IR as well as making "separated" encounters in the arcs, the situation becomes much harder to control. We have worked both with one bunch and with 3 bunches of e^-, against 3 of e^+, and find that the conditions yielding good luminosity in the single-bunch situation do not automatically extend to the multibunch case. The best so far obtained was a total luminosity of about 10^{31} $cm^{-2}s^{-1}$ at each IR for 3×3 bunches of about 8 mA each. This would be an encouraging start if an extrapolation to higher currents could be counted upon.

It is clear to us that establishing satisfactory multibunch conditions will be a major challenge, probably requiring the analysis and control of several unfavorable effects. However, there is consolation in the thought that much painstaking effort needs to go into the commissioning of any colliding-beam facility. One can probably summarize our present position by saying that we find ourselves with a *new* machine on our hands!

Acknowledgement

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[#] *Present address: SLAC, POB 4349, Stanford, CA 94305.*

[1] *J.Seeman et al., IEEE Transactions on Nuclear Science, NS-30 No.4, p.2033 (1983); J.Seeman, CLNS 82/531, Cornell University.*

[2] *The alternative of using pulsed magnetic elements, synchronized with the passage of different bunches, involves unattractively large power levels.*

[3] *Freon TF Solvent,* ® *E.I.DuPont de Nemours & Co., Inc.*

[4] *M.Billing, J.Kirchgessner, and R.Sundelin, IEEE Transactions on Nuclear Science, NS-26 No.3, p.3583 (1979).*

[5] *Model PG-150 N/P 6-M46, Glassman High Voltage, Inc., White House Junction, NJ.*

[6] *S.Myers, IEEE Transactions on Nuclear Science, NS-30 No.4, p.2466 (1983).*