LONG-RANGE BEAM-BEAM INTERACTION WITH THE BUNCH TRAIN OPERATION*

David Rice, CLASSE, Cornell University, Ithaca,NY 14853, USA
David Rubin, CLASSE, Cornell University, Ithaca,NY 14853, USA

Abstract

For the past three decades, colliders have realized increased luminosity by adding beam bunches beyond the traditional $N_{interaction\ points}$ / 2. CESR has operated since 1983 with pretzel orbits to realize substantial improvements in luminosity. In 1994 bunch trains with horizontal crossing angle were introduced. We review some of the fundamentals of the long-range beam-beam effects, including bunch trains, and suggest some guidelines in the design of a circular e+e- Higgs Factory.

MULTI-BUNCH OPERATION IN E+E- CIRCULAR COLLIDERS

Ideally a circular colliding beam facility should have full flexibility in number of bunches to maximize performance with attention to bunch charge limits (head-on beam-beam effects, TMCI and other single bunch effects), total current limitations (RF, instabilities), and beam-beam tune shift limits. There are, unfortunately, also effects on performance resulting from the choice of adding bunches.

Where separate rings are not practical, the counter-rotating beams share a common vacuum chamber and guide fields with separation at crossing points provided by electrostatic or RF separators. The resulting closed orbits are generally referred to as pretzel orbits (Fig. 1).

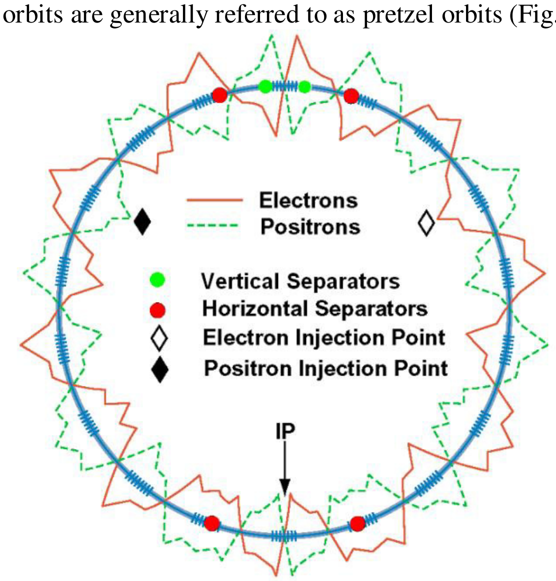

Figure 1: Pretzel orbits in CESR. Blue tic marks show crossing points for 9 trains of 5 bunches each.

Both the pretzel orbit and the multiple crossings where bunches experience the electromagnetic fields from the opposing beam impact the beam dynamics.

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PRETZEL AND PARASITIC CROSSING EFFECTS

Overview

We start with a brief outline of potential pretzel optics and parasitic crossing effects outlined in Table 1. The pretzel orbits themselves bring about multiple changes in optics. These are inherently different for electrons and positrons, but some effects are mitigated by choosing the appropriate symmetry in the ring.

The electromagnetic fields from the opposing beam cause multiple beam-beam effects (long range beam-beam interaction, or LRBBI) at each parasitic crossing. The effects of the LRBBI include kicks, tune and chromaticity shifts, and nonlinear coupling. The magnitude of the effects of these parasitic crossings depends on local pretzel amplitudes, twiss parameters and dispersion, as well as the charge in the opposing bunch and therefore do not affect all bunches uniformly.,. The variation of the lattice parameters at the parasitic crossing as well as the non-uniformity in the intensities of the opposing bunches makes mitigation difficult as compared with the usual head-on beam-beam effects, or impossible in many cases.

The distortion of the closed orbit distorts the optics of a single beam. If the separation scheme has the appropriate symmetry, the change in global parameters like tune and chromaticity is common to both beams. But local distortions are generally different for electrons and positrons. There is therefore a tension between minimizing pretzel effects (smaller pretzel amplitude) and minimizing LRBBI effects (larger pretzel amplitude).

Table 1: Pretzel and Long Range BBI Effects

Type	Source
Pretzel Optics	
Betatron phase errors	Sextupoles
Dispersion errors	Sextupoles
Damping partition #'s	Quadrupoles
Enhanced Synch. Rad.	Quadrupoles
H_V coupling	Sextupoles, etc.
Instr. Nonlinearities	BPMs
Parasitic Crossings	(Opposing beam -)
Orbit distortion	Far E&M fields
Coherent tune split	Far E&M fields
Nonlinearity	Core E&M fields
Chromatic Effects	Far E&M + Dispersion

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Pretzel Optics

Dispersion errors will be introduced at each quadrupole where the pretzel orbit is non-zero. Betatron phase, coupling, and dispersion errors are generated at each sextupole.. When separation is in the horizontal plane, the phase advance and horizontal dispersion will be affected. For vertical separation, coupling terms will be introduced along with vertical dispersion. Skew quadrupole components will in general generate out of plane dispersion. These effects are calculable and can be assessed early in the design stage. These effects are more easily addressed if they are the same for both beams, i.e. common changes in tune, chromaticity etc. Differential global effects can be reduced significantly by maintaining anti-symmetric pretzels as much as possible. Further correction may require introduction of additional quadrupole and sextupole and skew sextupole controls.

As the closed orbit passes through quadrupoles off center, in addition to enhanced radiation losses, the radiation damping is modified. The damping parameter D is modified approximately as [1]:

$$J_x \cong 1 - \frac{2\int K_1^2(s)(D_x - D_{x0})x_p(s)ds}{\int G^2(s)ds} \qquad (1)$$

resulting in changes in the horizontal emittance, ε_x that can be difficult to correct.

Synchrotron radiation losses will be enhanced as:

$$\Delta P_\gamma \propto \int K_1^2(s)\, x_p^2(s)\, ds \qquad (2)$$

Since the losses scale overall as E^4, the enhanced synchrotron radiation must be considered in the design of a Higgs factory.

In the following $d_{x,y}$ is design pretzel separation between beams at parasitic crossings and $x_{1,2}$ or $y_{1,2}$ is the displacement of a particle in beam 1 or 2 from the equilibrium orbit.

Horizontal to vertical as well as dispersion coupling is introduced by vertical displacements in sextupoles. The magnitude of this coupling depends on the separation scheme and alignment and field errors. Additionally the betatron phase errors previously described may compromise pre-existing coupling corrections.

The effects of large closed orbit displacements on instrumentation may be significant. Beam position detectors may exhibit significant nonlinear behaviour when the pickup electrodes have a spacing comparable to the peak-to-peak pretzel amplitude. In this case compensation must be made before using the data for correction or analysis. A map of measured positions against a background of actual beam (wire) positions is shown in Fig. 2.

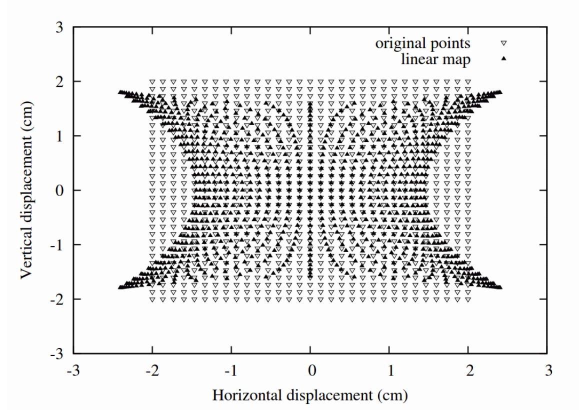

Figure 2: Nonlinear response of a CESR BPM against a background of actual positions.

Parasitic Crossings Beam-beam Effects

For reasonably large separation (>5σ) between opposing beams the angle imparted to a bunch during a horizontally separated passage is [2]:

$$\Delta x_1' = -\frac{2N_2 r_0}{\gamma_1 d_x} - \frac{2N_2 r_0}{\gamma_1 d_x^2}(x_1 - x_2) \qquad (3)$$

with a similar result in the vertical plane. The subscripts refer to the two beams, d_x is the nominal pretzel separation between closed orbits and x is the displacement from the closed orbit for each bunch.

The closed orbit distortion is the vector sum of the kicks from the first term on the RHS. This can give rise to position or angle errors at the primary interaction points.

The second term represents a variable deflection turn-by-turn depending on the bunches' oscillations about their equilibrium (pretzel) orbits, producing a coherent focussing force and coupling between the two beams. The tune shift parameter is then:

$$\Delta \nu_x^{(bb)} = -\frac{r_0 N \beta_x}{4\pi\gamma d_x^2} \qquad (4)$$

The coherent beam-beam modes resulting from these tune shifts are given by the eigenvalues and vectors of the single-turn matrix resulting from inclusion of all the parasitic crossings.

While the orbit distortions and coherent modes may produce operational problems, they generally will not result in excessive particle loss, particularly with a good bunch-by-bunch feedback system

If individual particles approach within 2 or 3 sigma of the opposing beam core the beam-beam kick will become very large since the beta functions at most parasitic crossing points are huge compared to a low-beta IR insert. Analysis and tracking studies have shown that, with horizontal separation, the vertical motion is most strongly affected, and particle loss is generally in the vertical beam motion. [3] Fig. 3 below shows tracking results for a separation of 6.5 σ_x between beams (bunch profile shown on RHS.).

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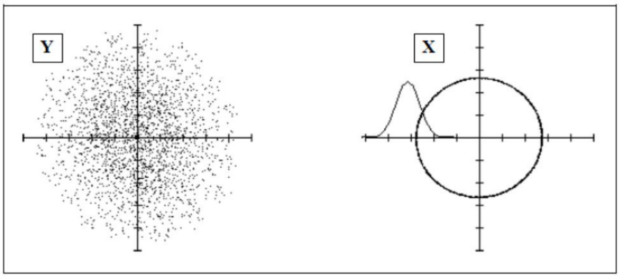

Figure 3: Phase space of particles tracked with 6.5 σ_x between beams. From reference [3]

The beam-beam tune shift will be modulated by the energy oscillations and local dispersion at the parasitic crossing points. Considering the horizontal plane only, adding the dispersion causes a modulation of the chromaticity as [4]:

$$\Delta\nu_x'^{(bb)} = -\frac{2D_x}{d_x}\Delta\nu_x^{(bb)} \quad (5)$$

The factor D_x/d_x can be quite large, leading to significant shifts in chromaticity depending on crossing point parameters and bunch intensities.

Minimum eparation equirements

As a general rule, all of the following separation requirements should be met [5]:

1. $d_i > n\sigma_i$ where $n \approx 5.5$-7
2. $\Delta\nu_x^{(bb)} < \Delta\nu_{max}^{(bb)}$
   where $10^{-4} < \Delta\nu_{max}^{(bb)} < 10^{-3}$
3. $\sum_i \Delta\nu_x^{(bb)} < \sim 10^{-3}$

(Horizontal parameters are shown, the same applies to vertical where relevant.)

Several plausible phenomenological models for minimum required separation were tested at CESR [6] with several optics configurations. Of note, the 4 (out of 11) best models all had a β_y dependence (with horizontally separated beams). CESR optics were designed to minimize both horizontal and vertical tune shifts at each of the parasitic crossings as well as to maximize separation. For operation with symmetric pretzels, differential path length, tunes, and partition numbers were constrained. Maximum tolerable individual and accumulated tune shifts were determined experimentally. Beam energy dependence emerged through the constraints on parasitic tune shifts.

BUNCH TRAINS

Once the bunch charge has reached the (head-on) beam-beam limit, beyond which luminosity increases only linearly with current, adding more bunches is desirable. If available anti-nodes of the pretzel are filled with bunch crossings (i.e., one bunch per beam per integer tune), increasing bunch numbers requires using closely spaced groups, or trains, of bunches. The trains must be short enough so the crossing points are all encompassed, with sufficient separation, between pretzel nodes.

Since we are trying to pack as many bunches as possible into each train, the parasitic collision points will be spread across each pretzel anti-node, generally resulting in a wider variation in beam-beam related parameters. Fig. 4 below shows the horizontal separation in units of σ_x in CESR during the 1990's. [7] Fig. 5 shows the vertical difference at the interaction point (coupling by experiment solenoid), and the tune shifts for the configuration in Fig. 4. Obviously compensating these effects bunch-by-bunch would be challenging. With the total flexibility in quadrupole/sextupole distributions in CESR it is possible to optimize these parameters. [8]

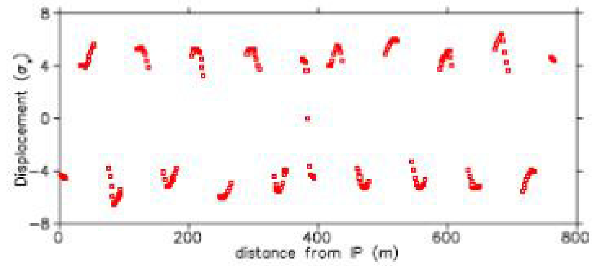

Figure 4: Horizontal separation at each parasitic crossing point with 9 trains of 5 bunches each in CESR. Beams are separated vertically at the point in the center.

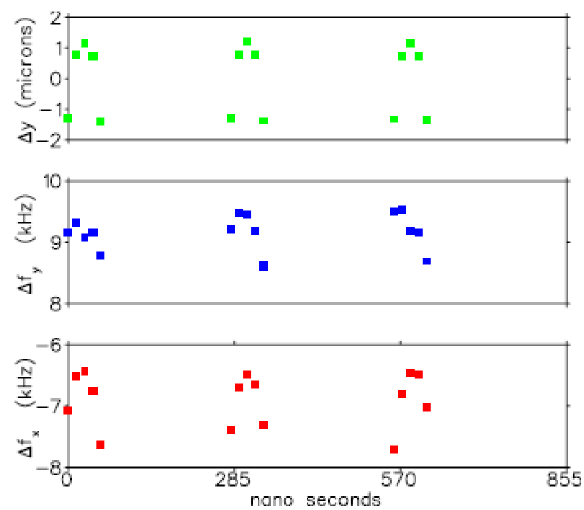

Figure 5: Vertical displacement at the interaction point and parasitic crossing induced tune shifts ($\Delta Q \times 390$ kHz) for a strong beam 9 trains of 5 bunches, each with 1.2 x 10^{11} e-. Only 3 trains are shown since there is a 3 train periodicity in the 9 trains. From reference [7]

There is also the issue of separation around the interaction point of a collider – common to both single and two-ring colliders. Several options have been used at various colliders, including crossing angle (CESR, DAΦNE, LHC), electrostatic separators (LEP, Tevatron), and for asymmetric energies, magnetic separation (KEK-B, PEP-II). The parasitic crossings around each interaction point introduce the same beam-beam phenomena as crossings in the arc. A crossing angle also introduces potential vertical errors at the interaction point if the detector has a strong solenoid field.

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If the single bunch current is limited by LRBBI, then adding more bunches may be helpful. One may ask, however, if the effects of closely-spaced parasitic crossings add coherently, nullifying the advantage for LRBBI.

If the parasitic crossings in a train have a coherent LRBBI then current limits will scale only as the total train current, I_t. If they are incoherent, then the scaling would be as $I_t/\sqrt{N_{bt}}$. (N_{bt} is the number of bunches in the train.) Measurements were made at CESR [9] to give guidance for limits to bunch train spacing from effects of coherency between bunches. A weak probe bunch experienced multiple parasitic crossings (but no head-on collision) from a drive beam consisting of one of three configurations: 1) a single bunch; 2) two bunches with separation 14 ns; 3) two bunches with separation 28 ns. The minimum pretzel amplitude for ~50 minute lifetime vs. total drive train current was recorded. Results are shown in Fig. 6 below.

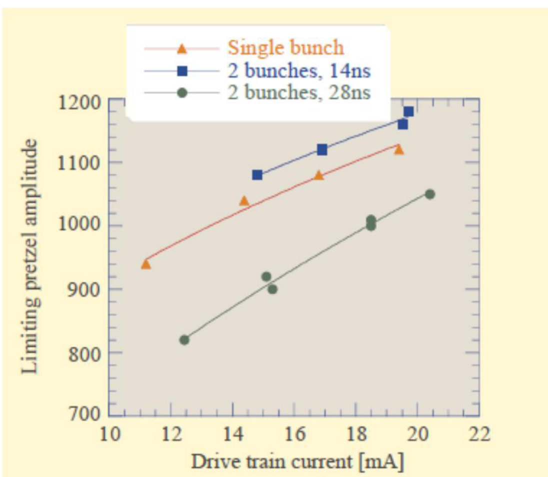

Figure 6: Pretzel amplitude for 50 minute lifetime of a test bunch interacting with opposing drive beam. Coherency between interactions becomes significant between 28 and 14 ns separation. From reference [9].

MITIGATION OF PRETZEL AND LRBBI EFFECTS

Mitigation of Pretzel Effects

Mitigation of pretzel effects begins with designing anti-symmetric pretzels, or as nearly so as possible with respect to the interaction points. This will reduce the differential effects of pretzels such as orbit kicks, but leaving a possible crossing angle.

Strategically placed sextupoles can control the tune splitting of the two beams as well as dispersion errors. CESR conveniently has independent control of all sextupoles and quadrupoles, permitting substantial compensation of $\Delta\nu_x^{(bb)}$, variation of J_x, crossing point angle, "pretzel efficiency" (separation at parasitic crossings relative to peak pretzel closed orbit), and an empirical figure of merit $\sum_i \epsilon_x \beta_{xi} \beta_{yi} / x_i^2$ [8]. Sextupoles are optimized to minimize local chromaticity, optics variation with closed orbit (pretzel), and amplitude dependence of optics, including coupling.

However, CESR is the only ring with pretzels that has the luxury of independently controlled quadrupoles and sextupoles. Selected sets of quadrupoles and achromatic sextupoles were used to compensate pretzel effects in LEP. [10,11] In addition, vertical trim separators and separator scans minimized orbit differences at interaction points. As with most colliders, fine tuning to achieve "golden orbits" is necessary to realize peak luminosity.

Mitigation of LRBBI Effects

Given sufficient flexibility in sextupole configuration, the coherent LRBBI effects may be effectively reduced by splitting the betatron tunes for the two beams beyond any coherent tune shift from parasitic crossings. This is routinely employed at CESR. [12] The perturbation to vertical motion by LRBBI may be reduced by increasing the vertical emittance of the "strong" beam. While this may help during injection, it is not necessarily productive for maximum luminosity. Effective bunch-by-bunch feedback can help damp residual coherent motion.

Observing that the magnetic field from a wire next to the beam mimics the LRBBI field, use of such a wire to compensate the parasitic crossings was suggested for hadron colliders [13] and has been extensively modelled. Some experimental investigation has been carried out with inconclusive results [14]. Fields from wires have also been used to simulate parasitic crossings effects. [15] We mention in passing that electron beam lenses for hadron colliders have been investigated at the Tevatron with some success. [16,17]

Wire compensation for lepton colliders has been studied and tested at DAΦNE [18]. While some improvement in lifetime of the traditionally weak beam was obtained in one configuration, no benefit was found in a second configuration of the interaction region.

With individual control of quadruples, it may be possible to mitigate parasitic crossing effects by changing focussing local to each parasitic crossing as a function of bunch currents. This was modelled and tested at CESR [19] with some success, using the calculated focussing at the core of the "weak" bunch. Models showed some increase in dynamic aperture, and a 20% increase in beam current was obtained in a test configuration emphasizing the parasitic crossing limitations compared to the head-on BBI. This configuration was not optimum for luminosity however.

LRBBI IN CIRCULAR HIGGS FACTORIES

The choices for mitigation of parasitic crossing effects in large circular colliders are limited, or at least more difficult, compared to the lepton machines discussed above.

Since extensive installation of trim or compensating elements will be costly, a solid program for modelling the

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optics and beam dynamics is essential, and a sizable part of the R&D effort should be budgeted for modelling and simulations.

The LEP experience is most relevant for the size (energy) of the ring. The beam lifetime in a Higgs Factory precludes low energy injection so this is one LEP effect that will not have to be managed.

Compensating quadrupole families and achromatic sextupole groups will likely be essential, as will trim of differential beam positions.

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