INJECTION WITH PRETZELS AT CESR*

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Abstract

CESR has operated with pretzel orbits since 1983. With separation in the horizontal plane, the parasitic crossings reduce the acceptance for horizontal betatron stacking of injected particles. Furthermore, both coherent and incoherent long range beam-beam effects reduce tune plane working space. Each bunch will have a particular coherent tune shift depending on parasitic crossing points and bunch currents in the opposing beam. We present the experience at CESR and discuss applicability to the circular Higgs factories.

CESR RING AND INJECTOR

CESR operated as an electron-positron collider from 1979 to early 2008. Ring and injector parameters are listed in Table 1. The synchrotron ring circumference is precisely 60/61 times the CESR circumference, permitting filling of many CESR bunches each injector cycle.

Table 1: CESR Ring and Injector Parameters

Parameter & Units	Value
CESR Ring	
Circumference [m]	768.44
Operating beam energy [GeV]	1.8-6
Transverse damping time [ms]	24
Current per beam (mA)	400
Number of bunches	40
RF Frequency [MHz]	499.7594
CESR Injector	
Injector repetition rate [/s]	60
Linac Energy (e+/e-) [MeV]	160/300
Linac max bunch number	24
Linac charge/bunch (e+/e-) [nc]	
Linac RF frequency [MHz]	2855.77
Synchrotron Circumference [m]	755.84
Synchrotron RF frequency [MHz]	713.943
Highest common frequency [MHz]	71.394
Smallest common bunch spacing [ns]	14.007

The numerology of the various RF systems in the injector chain enables acceleration and injection of bunches spaced at 14 ns intervals (7 CESR RF buckets) in a single injection cycle. The maximum number of bunches is limited to about 24 by loading of the linac RF accelerating cavities. Intercalary buckets may be filled by shifting the injector RF phases between injection cycles. Bunch currents in CESR are monitored and the linac bunch pattern adjusted to equalize the bunch currents.

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Figure 1 below shows a layout of the CESR accelerator complex. Two important features of CESR are critical to optimization of injection with pretzeled orbits:

1. All quadrupoles and sextupoles are independently powered, enabling total flexibility in designing optics and creating group knobs for orthogonal adjustment of specific accelerator physics parameters.
2. The linac/synchrotron provide trains of bunches each (60 Hz) cycle for rapid filling in multi-bunch mode.

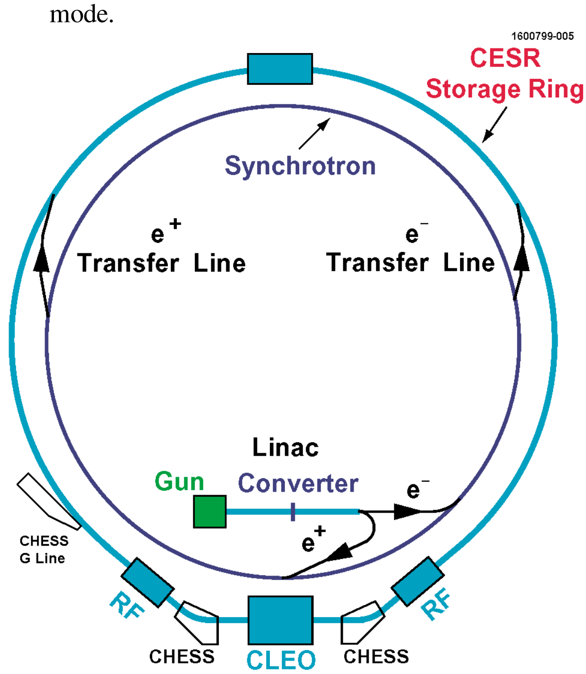

Figure 1: CESR accelerators layout.

Injection into CESR takes place, nominally at least, in the horizontal plane. The beam is extracted from the synchrotron in a single turn by a fast (2.5 μsec) kicker and a pair of septum magnets to bring the beam through the synchrotron fringe field into transfer lines shown above. The transfer lines (Figure 2) have five quadrupoles each (two of them off-center), three horizontal bending magnets and two or three steering trim magnets in each plane. A pulsed septum magnet provides a final bend to bring the injected bunches roughly parallel to the stored beam that has been brought next to the septum magnet by three pulsed kicker ("bumper") magnets forming a closed orbit bump. Injection efficiency can be as high as 90% for a single beam, but is reduced significantly in the presence of a counter-rotating beam as described below.

When all of the beam sizes and hardware parameters are accounted for, the center of the injected bunch has an

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oscillation amplitude about the closed orbit of about 2.2 mm/$\sqrt{\beta}$ or about +/- 12 mm for a typical focussing quadrupole.

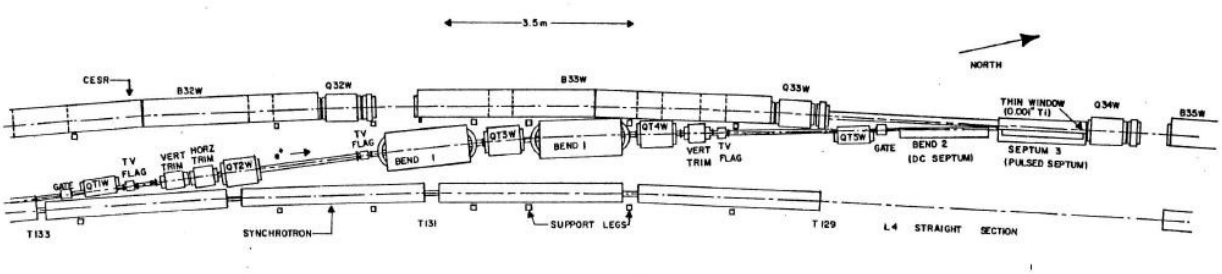

Figure 2: CESR west (positron) transfer line layout.

PRETZEL ORBITS

Pretzel orbits are established by four horizontal electrostatic deflectors placed roughly as shown in Figure 3. The peaks of the pretzel are roughly ±20 mm in the 90 mm full horizontal aperture vacuum chamber. This geometry is illustrated in Figure 4.

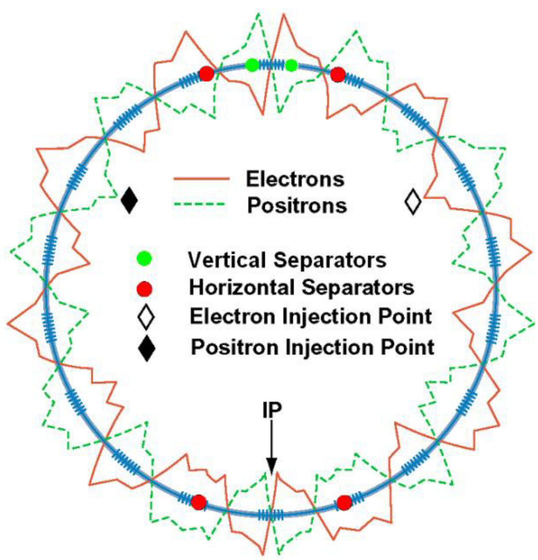

Figure 3: Pretzel layout of CESR with ±3.5 mr crossing angle in the IP and vertical separation in the opposite IP.

Storage ring optics are optimized to maximize the "pretzel efficiency" or minimum separation at the crossing points divided by the peak pretzel amplitude, both normalized to $\sqrt{\beta_x}$. Using bunch trains, up to 9 trains of 5 bunches each, necessarily reduces the pretzel efficiency since the crossings cover an appreciable part of each pretzel anti-node, pushing toward the nodes. Figure 5 below shows the separation at parasitic crossings in units of horizontal beam size for the 9 train x 5 bunch configuration.

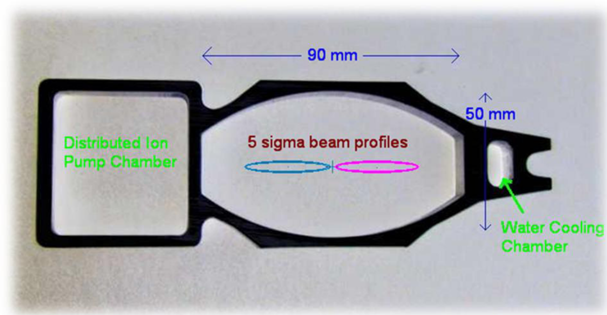

Figure 4: CESR's vacuum chamber showing relative position and size of beams at a crossing point.

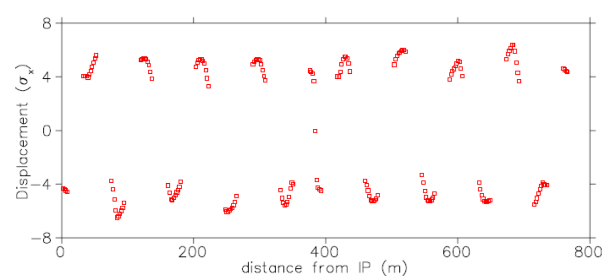

Figure 5: Separation at parasitic crossing points in units of σ_x. [1]

When the injection oscillations are included, it is clear that some of the electrons occasionally pass close to the core of the opposite beam until they damp. In fact the injection efficiency drops significantly. The clearances between injected bunches and the counter-rotating bunches at each parasitic crossing were calculated for CESR 1.9 GeV conditions and are shown in Figure 6. Clearly the bunches that have crossings at 380, 590, and 630 m azimuth will likely be difficult to fill.

INJECTION WITH PRETZELS

With a single beam in CESR the injection efficiency was typically 50% to 80%, occasionally approaching 100%. With a full counter-rotating beam present, the efficiency dropped to 20%-30% in the best of conditions, and below 10% in bad. Generally certain bunches,

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usually at the end of trains, dominated the injection losses.

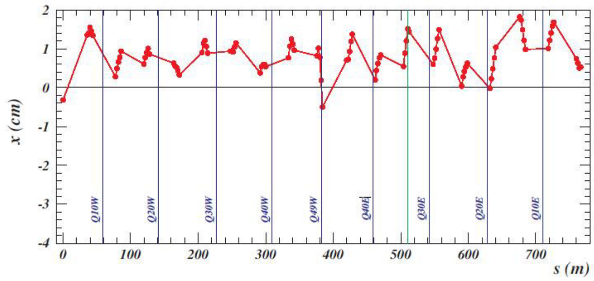

Figure 6: Clearance of injected electrons from stored positron beam (CESR 1.9 GeV, 9 trains x 5 bunches each). [2]

Several steps [2] to mitigate the LRBBI effects were taken, beginning with separation of electron and positron betatron tunes to avoid variable bunch-to-bunch coherent effects. This was easily achieved at CESR by creating a group knob control of sextupoles to change the two beams' tunes differentially while maintaining chromaticity and minimizing large local optics perturbations. Tune differences of 0.025 are generally used.

Beam losses from the LRBBI are primarily in the vertical dimension. [3] The vertical size of the "strong" beam plays a fundamental role in driving resonances. By placing the horizontal and vertical tunes near a coupling resonance, the vertical emittance is increased and horizontal decreased, both desirable in reducing the parasitic crossing effects. The application of this technique may have to be limited to avoid compromising luminosity.

A one-turn kicker, or "pinger" is frequently used to decrease the amplitude of oscillation of the injected beam within a few turns after transfer to the storage ring. The small increase in stored beam motion is generally inconsequential.

We have used mismatch of energy between the injector and storage ring to share horizontal and longitudinal phase space during injection. Empirical exploration has generally been more successful than detailed modelling.

Bunch-by-bunch beam stabilizing feedback decreases the damping time of coherent motion resulting from errors in pulsed element amplitudes and timing as well as the pinger mentioned above.

Allowing vertical ripple from the interaction region separators to propagate around the arcs was used when effective to vertically separate beams at particularly bad crossing points.

When initially injecting, it is sometimes helpful to fill one beam evenly to half current then the other, finally returning to the first.

We have only rough experimental information regarding energy dependence of LRBBI effects. When operations transitioned from B to Charm physics (beam energy 5.3 GeV to 1.9 GeV) the LRBBI effects were proportionately greater, lowering maximum sustainable current per beam from 375 to 75 mA during colliding beam operation. 1.8 T wigglers controlled horizontal emittance and kept damping times within a factor of 2 compared to 5.3 GeV operation.

While acceptable conditions usually persisted with minor adjustments once achieved, equipment failure or extended shutdown periods would sometimes require extended tuning to recover performance. Good injection was dependent on filling profiles of bunches in each beam. Some irregular profiles would exacerbate losses or decrease the injection rate of the opposing beam. This is not unexpected given the bunch-by-bunch dependence on individual parasitic crossing parameters and opposing beam bunch currents.

HIGGS FACTORY INJECTION

Of the mitigation measures used at CESR, several may be applicable to a Higgs Factory circular collider.

1) Splitting tunes of the two beams is feasible if appropriate sextuple control is available.
2) Control of vertical emittance may be possible depending on beam-beam parameters, but separate conditions for injection would require fast pulsed elements.
3) A pinger to share oscillation amplitudes between stored and injected beams may be useful.
4) Energy mismatch should be considered.
5) Bunch currents should usually be kept as even as possible.

A two-ring machine will still have parasitic crossings near the interaction points, especially at lower energies where more (~10,000) bunches are optimum. Here other options such as vertical separation might be considered.

REFERENCES

Note: References from conference proceedings (PAC, EPAC) may be found at http://jacow.org

[1] D.L. Rubin et al., "CESR Status and Performance," PAC 2001, Chicago, p, 3520

[2] M.G. Billing, J.A. Crittenden, M.A. Palmer, "Investigations of Injection Orbits at CESR Based on Turn-by Turn BPM Measurements," PAC 2005, Knoxville, p. 1228

[3] A.B. Temnykh, D. Sagan, "The Incoherent Long Range Beam-Beam Interaction in CESR," PAC 1997, Vancouver, p. 1768

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