Long-Range Beam-Beam Interaction with the Bunch Train Operation

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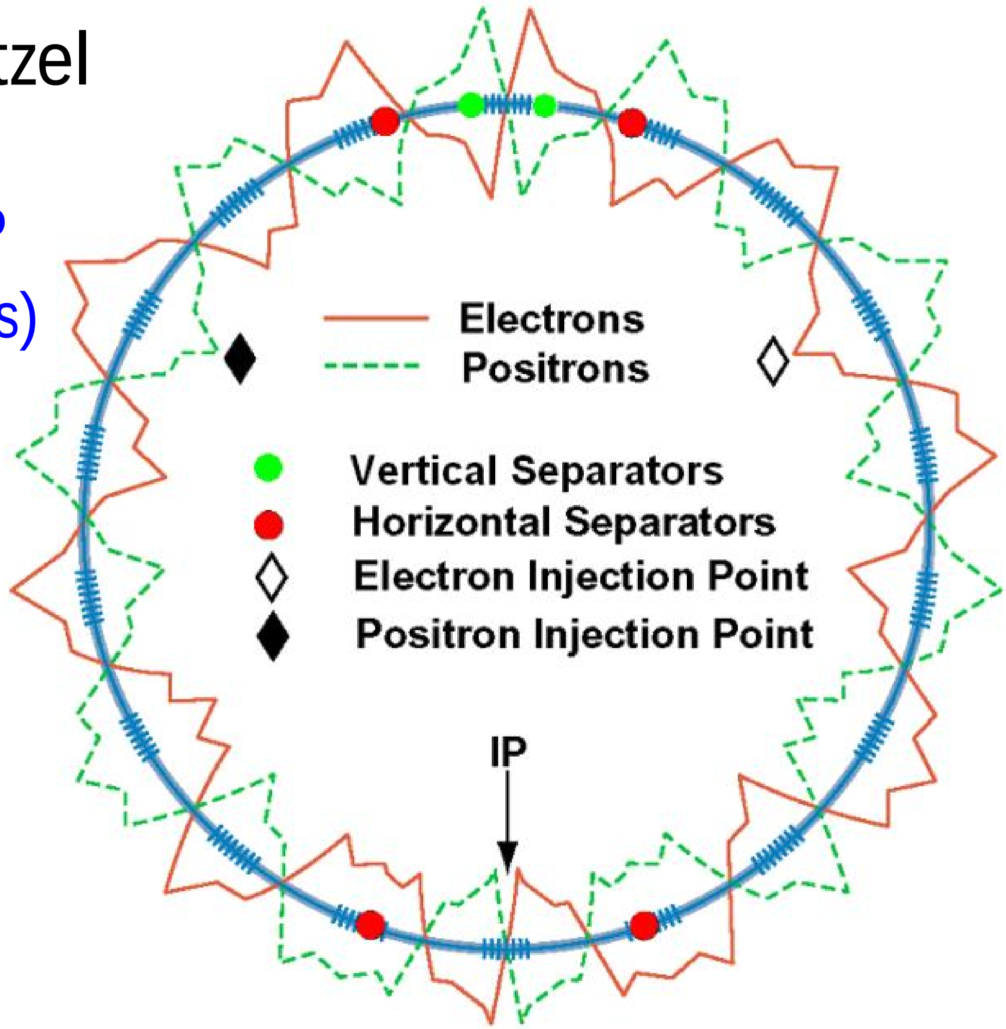
Pretzels and Bunch Trains

- Once per-bunch parameters have been optimized, we add bunches to maximize machine performance
- One or two rings?
  - Both have bunch train related challenges around the interaction point
  - Cost (initial and operating) usually favors one ring
  - Beam dynamics favors two rings at lower energy, to be determined (this week?) at Higgs energies.
- Define bunch train as having more bunches than integer horizontal tune – i.e., more than one parasitic crossing between pretzel nodes.
- Bunch trains have all the effects of pretzel-separated PC's plus some, so start with a quick review of pretzel optics and long range beam-beam interactions (LRBBI)

Pretzel Optics

- CESR pretzels with Q_x=10.6
- Optics errors from pretzel optics effects:
  - Displacements at the IP
  - Betatron phase (6-poles)
  - Dispersion (4, 6 poles)
  - Damping partition #'s (4,6-poles)
  - Enhanced synchrotron radiation (4 poles)
  - H-V coupling (6-poles)
  - Instrumentation (BPM nonlinearities)



Mitigation in CESR

- It is clearly important to reduce the harmful effects of both pretzel orbits and the LRBBI where possible.
- While CESR has been somewhat successful with bunch trains in pretzel orbits for 3 decades, two very important things must be kept in mind:
  1. The independent control of all quadrupoles and sextupoles provides opportunities for detailed compensation and control of most of the pretzel effects and some of the LRBBI effects. This is not practical in large rings.
  2. Living with pretzels near limit of performance is a CONSTANT STRUGGLE!

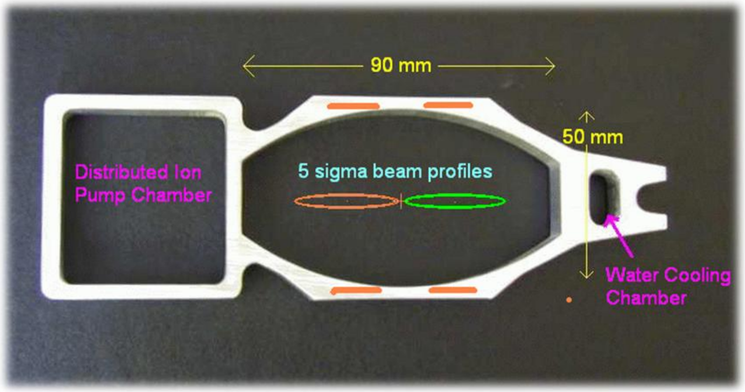
Mitigating Pretzel Optics Effects

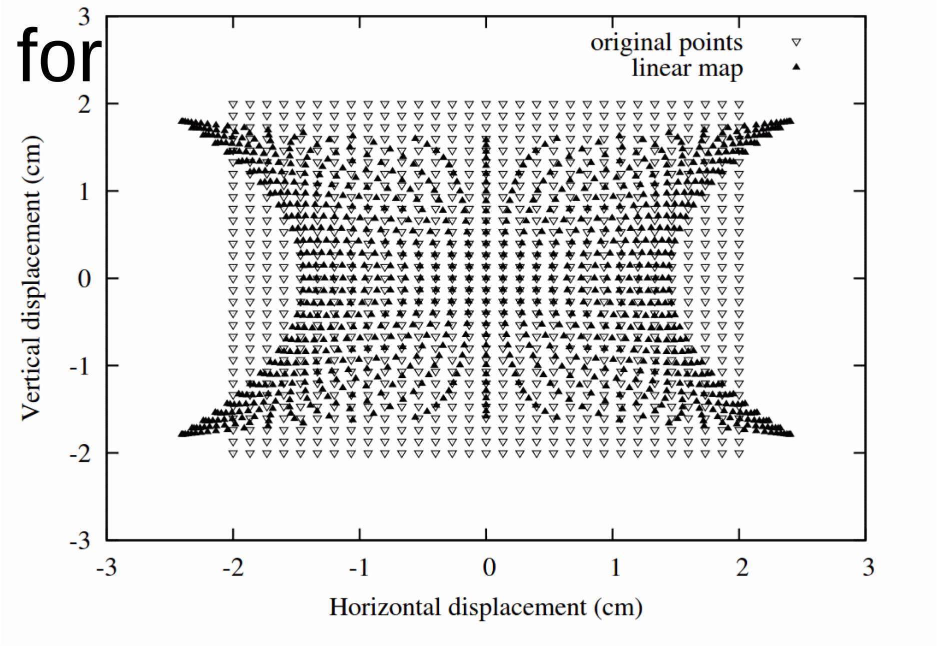
- Pretzel anti-symmetry
  - Anti-symmetric (about the interaction point) pretzels are usually easiest and most effective mitigating measure, reducing the first 3 effects previously listed.
- Electrostatic trim elements
  - Reduce any differential displacements at the IP
- Trim quadrupoles for phase correction/pretzel closure, damping control
- Trim achromatic sextupoles for differential phase correction, “tonality” control
- Skew sextupoles for differential coupling correction

Pretzel Effects - Instrumentation

- Pretzel orbits may require careful correction of inherent nonlinearities in beam position pickup.
- Good time response with minimal cross talk between adjacent bunches is needed for online orbit measurement.

- From the above, good modeling coordinated with design effort is critical.





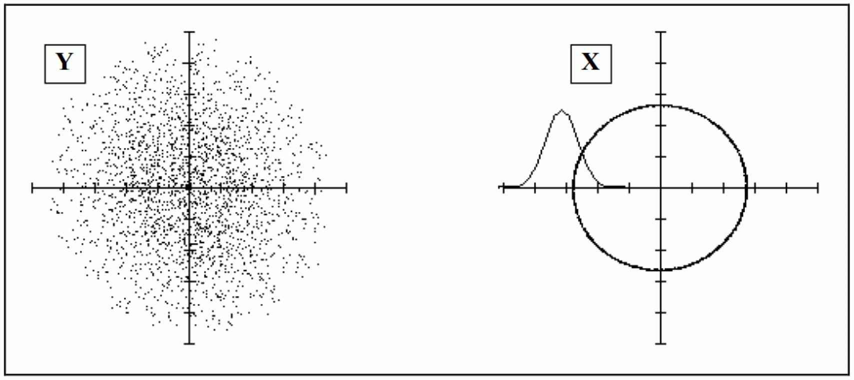
Parasitic Crossings

- a.k.a. - Long Range Beam-Beam Interactions (LRBBI)
- Basic coupling: $\Delta x_1' = -\frac{2N_2 r_0}{\gamma_1 d_x} - \frac{2N_2 r_0}{\gamma_1 d_x^2}(x_1 - x_2)$
- Dipole kicks add to closed orbit distortion – vector sum from the parasitic kicks in the ring
- Second term is focusing – in the case of horizontal separation defocus in *x*, focus in *y*. Resulting tune shift:

$$\Delta\nu_{x,y}^{(bb)} = (-,+)\frac{r_0 N \beta_{x,y}}{4\pi\gamma d_x^2}$$

Parasitic Crossings (cont.)

- The high (compared to IP) β_y at the PC's in the arc result in comparatively huge gradients & $\Delta\nu_y$. Particle loss is in the vertical dimension as shown by tracking:



Temnykh, Sagan, PAC May, 1997, Vancouver, p. 1768

- There is also synchro-betatron coupling when dispersion is present at PC's:

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

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Designing for LRBBI Effects

- General rule for pretzel separation requirements*:
  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. $\sum_i \Delta\nu_x^{(bb)} < \sim 10^{-3}$

- Also of note, an experimental evaluation** of various proposed models of LRBBI to maximize multibunch stored current w/>50 min lifetime found that the top 4 out of 11 models all minimized β_y at the PC's.

* Jowett in Handbook of Accelerator Physics and Engineering, World Scientific,1999
** Temnykh, Welch, Rice, PAC 1993, Chicago, p. 3520

Designing for LRBBI Effects

- At CESR, optics optimization for PC BBI includes minimizing*:
  - Maximum of any one $\Delta\nu_{x,y}^{(lrbb)}$
  - Total and spread of $\Delta\nu_{x}^{(lrbb)}$ for each bunch
  - $\sum_i \epsilon_x \beta_{xi} \beta_{yi} / d_{xi}^2$
  - Pretzel dependence of *D* – damping partition #
  - Crossing angle at IP
- And maximize
  - d_{xi} (min) (i.e., maximize minimum separation at all PC's)
  - Pretzel Efficiency ≡ $\min[\frac{d_i/\sqrt{\beta_{xi}}}{x_{max}/\sqrt{\beta_{x,max}}}]$

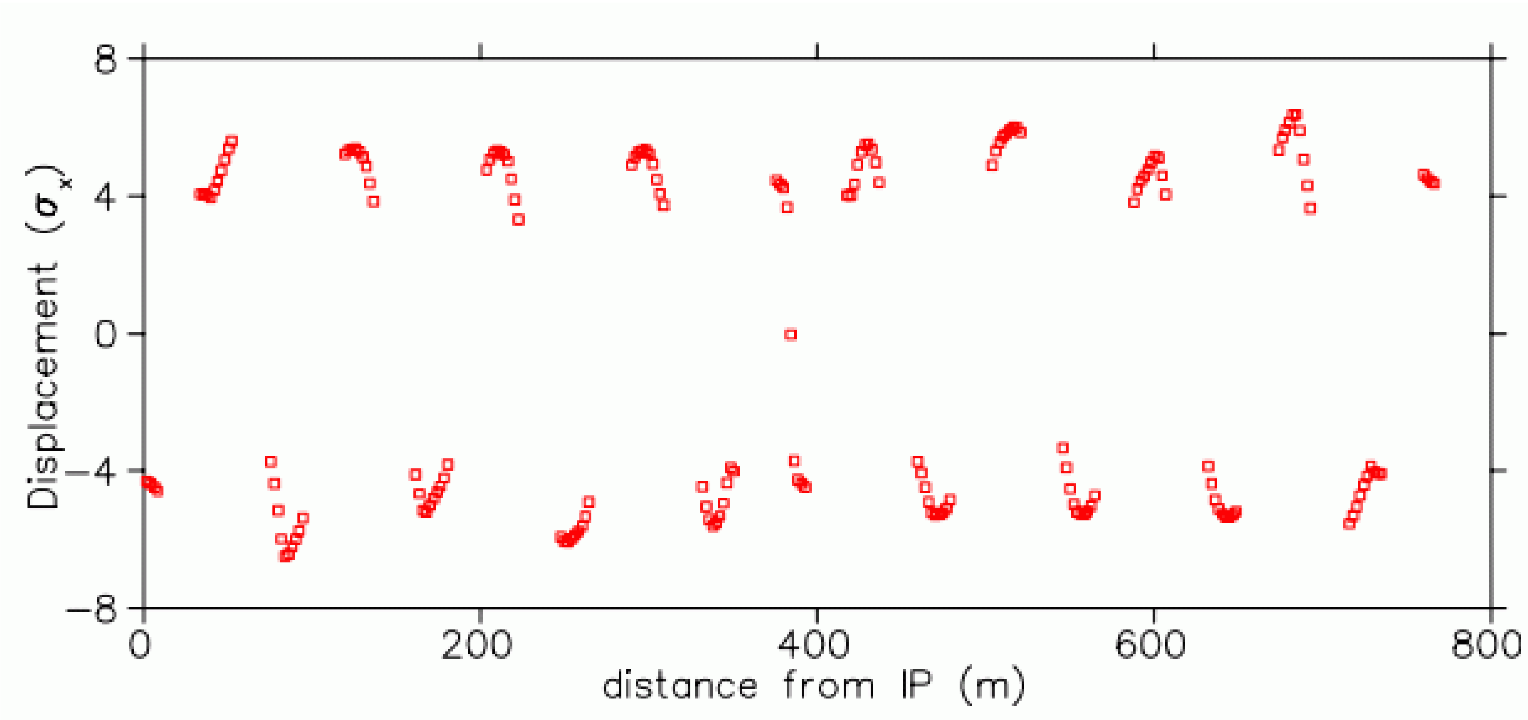
* D. Sagan, D. Rubin, "CESR Lattice Design," PAC June, 2001, Chicago, p. 3517

Bunch Trains

- Once optimization of collider performance requires more bunches than INT(Q_x), one must add trains of bunches, with multiple PC's between pretzel nodes.
- Designing for bunch trains brings in only a few additional considerations beyond the LRBBI/PC effects discussed above.
- Having several PC's between pretzel nodes, or near IP, necessarily implies differences in separation and optics functions for different bunches.

Separation in CESR

Pretzel displacement in units of σ_x for 9 trains of 5 bunches each in CESR (D.L. Rubin, PAC, 2001, Chicago, p. 3520) Currents ~375 mA/beam @5.3 GeV

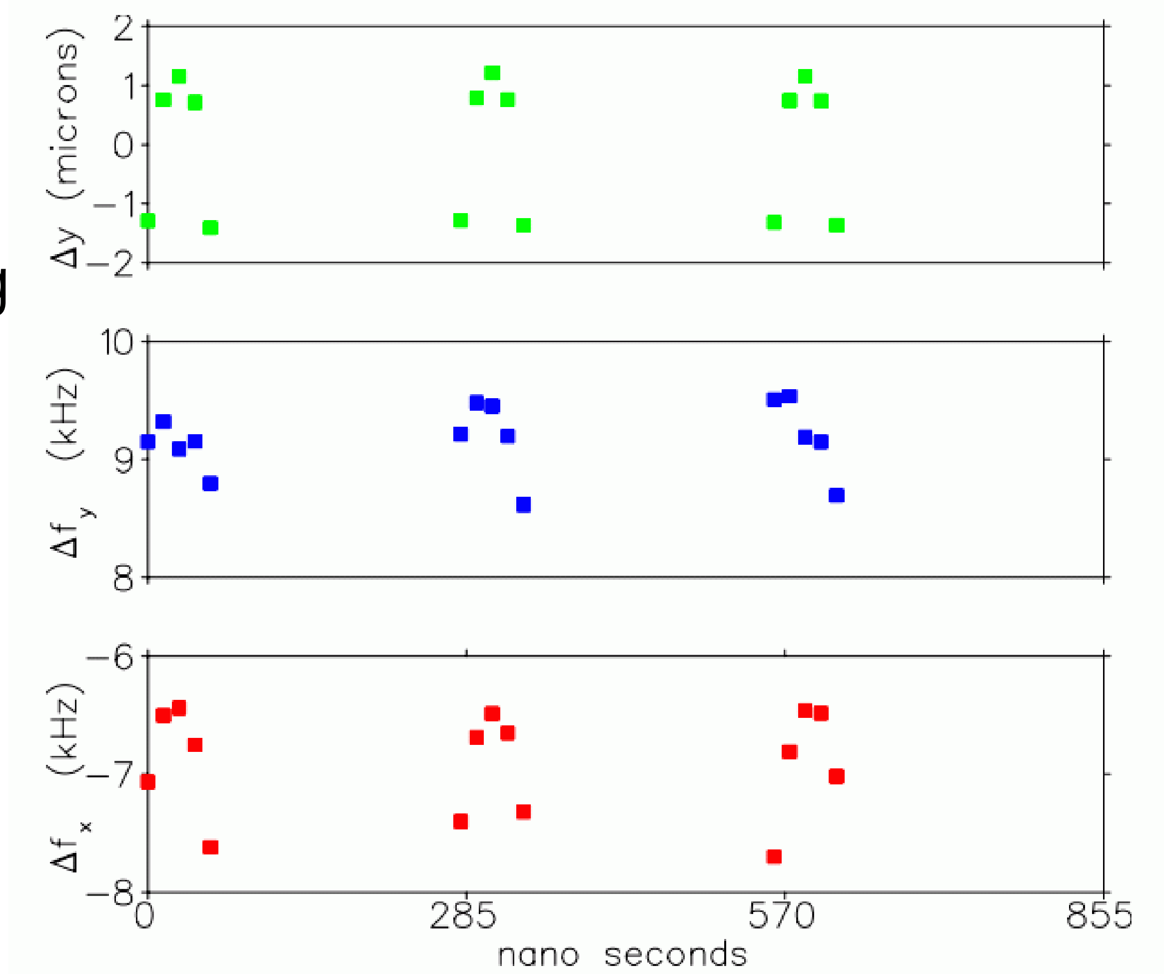


Luminosity Influences

Vertical orbit position change at IP and shift in betatron tunes from PC BBI. Currents ~375 mA/beam @5.3 GeV

Vertical orbit shift is coupled from horizontal crossing angle by experi-ment solenoid.

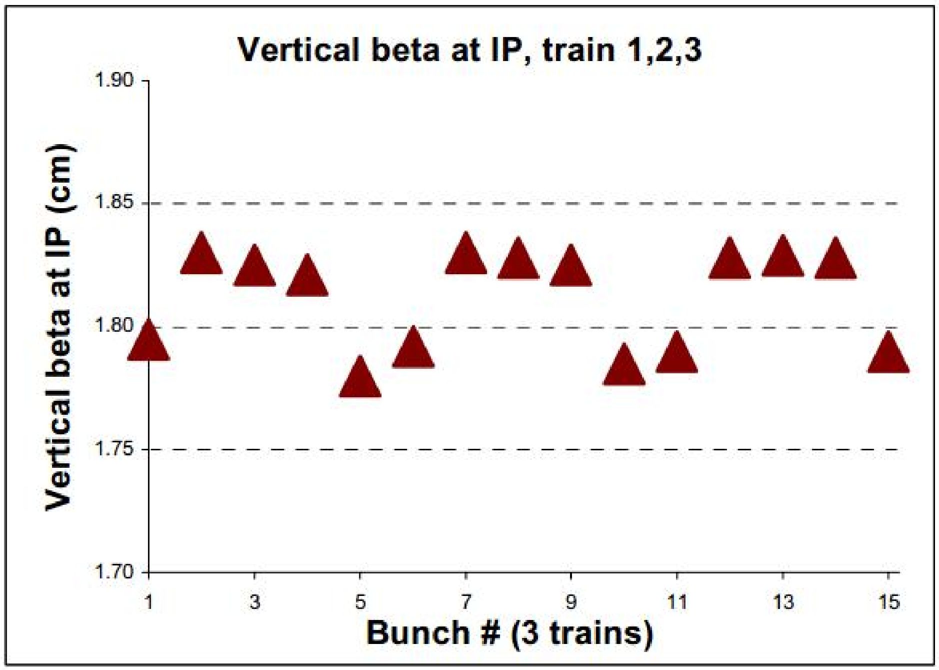
9 trains of 5 bunches each. (Because of 1/3 circumference periodicity, only 3 shown.)

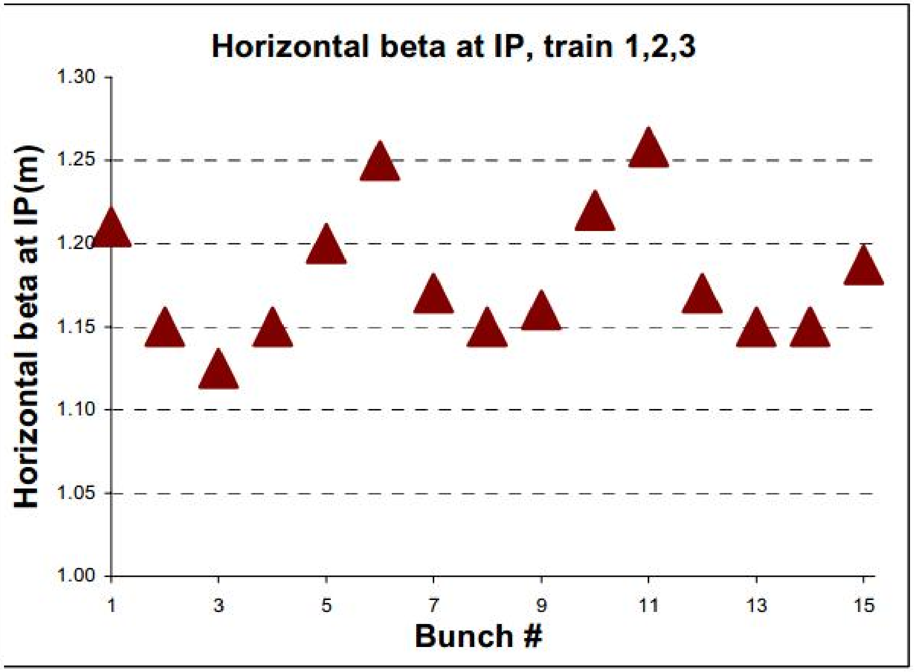


IP Beta variations

- Change in $\beta_{y,x}$ at IP due to CESR PC effects. (3 trains shown of 9, 5 bunches each, ~300 mA/beam)

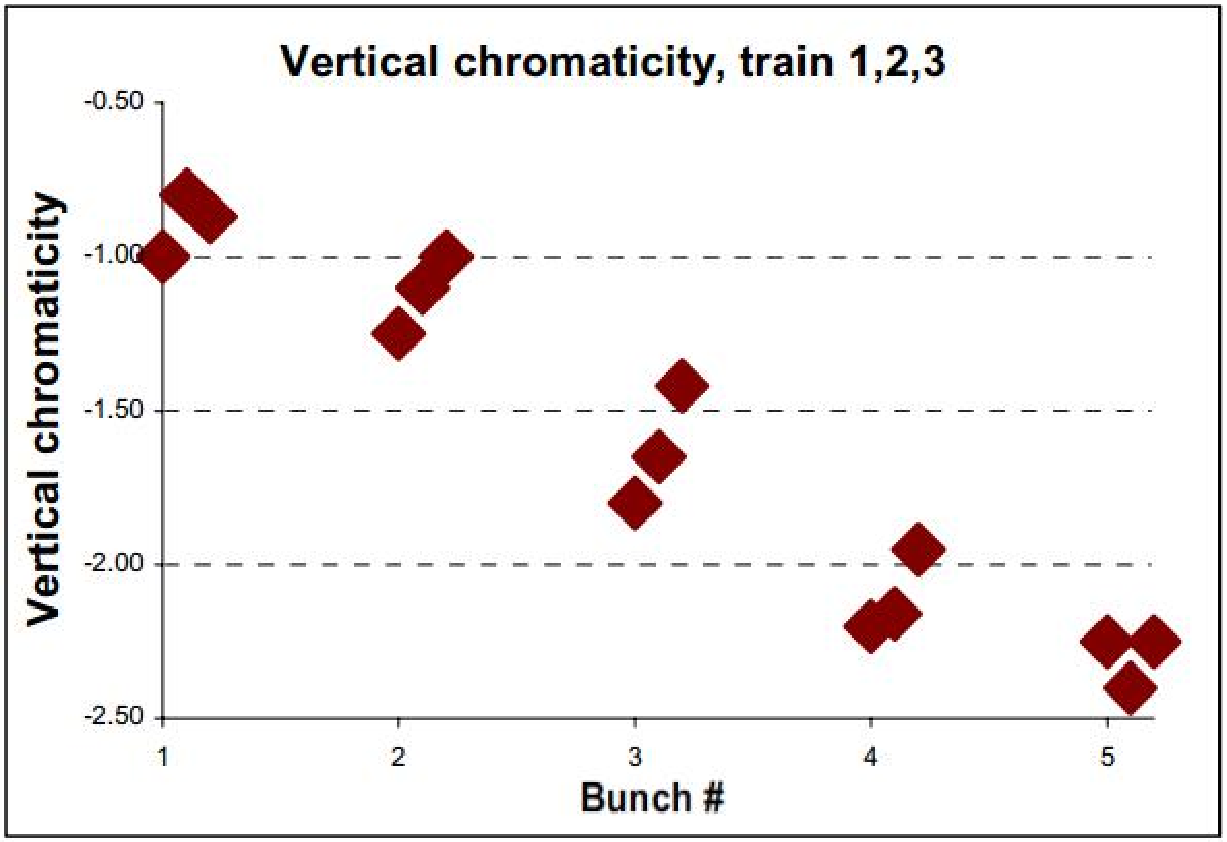
(Wang, Rubin, Sagan, PAC 2001, Chicago, p. 1999)





Chromaticity Variation

- Chromaticity also affected (same conditions as above)
- Horizontal change about half of the vertical.

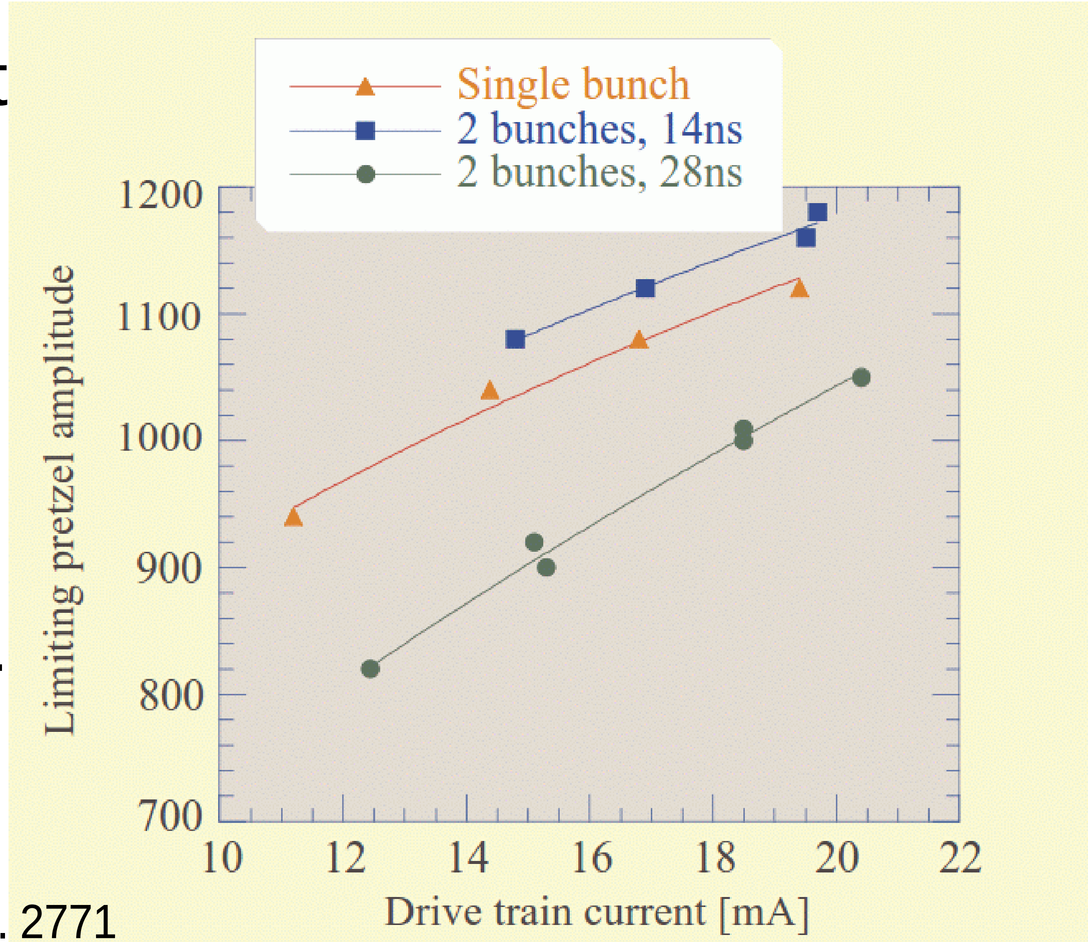


Coherency

- As the inter-bunch spacing within a train decreases, we would expect the PC interactions to become more coherent.
  If coherent, current limits have no dependence on N_b, otherwise

  $$I_{train,max} \propto \sqrt{N_b}$$

An experiment* at CESR gives some guidance (50 min lifetime threshold).



* Temnykh, Welch, PAC 1995, p. 2771

Bunch Trains near Interaction Points

- In either one or two rings PC's near IPs can be a problem.
- Separation methods include:
  - Electrostatic separators (LEP, Tevatron)
  - Magnetic Separation (PEP-II)
  - Crossing Angle (CESR, DAΦNE, KEK-B, LHC)
  - Crab Waist (DAΦNE)
- The crossing angle in Crab Waist is large enough that PC's are not problem. All other methods generally have several relevant PC's.
- Except for possible complications from the experimental solenoid field, analysis and mitigation follows closely that for arc PC's.

Mitigation of LRBBI

- Beam loss is generally in vertical phase space – enlarging "strong" beam vertical size can weaken BBI.
- Splitting e+, e- tunes can weaken coherent (and other?) effects.
- At CESR it is sometimes helpful when first filling the ring to partially fill one beam, then the other, finally come back to the first.
- A strong program of modeling of all important optics and beam dynamics of the proposed collider is critical to guiding design decisions.

Thank you for your attention.