Crossing Angles at CESR, Experiments and Experience

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Operational Experience

The highest priority of modern colliding beam storage rings to produce the maximum of number particle collisions. The rate of these collisions is proportional to luminosity and may be written in the following way:

$$L = 2.17\,(1+r)\,E_{beam}\frac{\xi_v}{\beta_v^\star}I_{beam}$$

Where L is the luminosity in units $10^{32}cm^{-2}s^{-1}s^{-1}$, r is the beam aspect ratio at the collision point, E_{beam} the beam energy in GeV, ξ_v the beam-beam tune shift parameter, $\beta_v^\star$ the beta function at collision point and I_{beam} is the average single beam current in amperes.

Our strategy for increasing L is described in reference [1]; here we will reiterate the main points. Provided the single bunch current can be kept at a reasonable high value so that a good tune shift parameter can be obtained, we are attempting to:

- increase the number of bunches.
- reduce $\beta_v^\star$ and the bunch length

These two tactics are relatively independent.

The historical view of $\beta_v^\star$ variation and variation of number of bunches per beam since start of operation in 1977 and up to now is shown on figure 1 One can see two steps of $\beta_v^\star$ reduction in 1981 and in 1986. These are explained in reference [2]. Now (1995) $\beta_v^\star$ is 1.8 cm, which is approximately equal to bunch length.

In 1981 after electrostatic separators were installed, CESR started operation in multibunch mode. From 1982 to 1988 CESR ran with 3 bunches per beam. The number of bunches in this period was limited by an RF problem. In 1988, after the problem was solved, the number of bunches was increased to 7 per beam. Further increases in the number bunches did not occur until a configuration of bunch trains with a crossing angle was implemented in 1994.

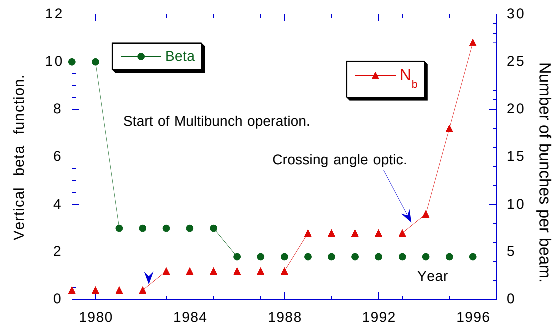

Figure 1: Evolution of β_v^* and the number of bunches per beam at CESR

The main idea of the bunch train is illustrated on figure 2. An angle between the two beams at the main interaction point translates to good beam separation in a short distance. This allows a dramatic reduction in the distance between bunches and therefore an increase in total number of bunches. Note that crossing angle or space between bunches must be big enough to provide suitable reduction of beam-beam interaction at the crossing point nearest to the IP. Closely spaced bunches are grouped in trains to maintain good separation in the arcs using the ordinary pretzel scheme for 7 bunches.

One can see three critical issues involved in bunch trains and crossing angles.

- The beam-beam interaction is modified by the crossing angle.
- The long-range beam-beam interactions are increased.
- The separation pretzel exists everywhere.

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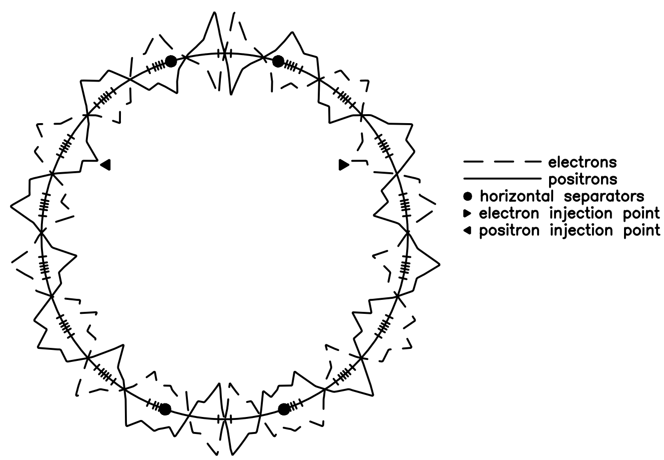

Figure 2: Crossing angle scheme at CESR

After two years of intensive experimentation and modifications to CESR we have analyzed these issues and overcome their limitations. It was shown that ±2.5 milliradian crossing angle in horizontal plane does not significantly affect the beam-beam tune shift parameter. Analysis of long-range beam-beam interaction experiments allowed us choose criteria for adequate beam separation, which was incorporated into optic design, and reduced the required physical separation so that only a 2.3 mr crossing angle is needed. Nonlinearities in the magnets, particularly the wiggler magnets which previously were not in the pretzel, were much more severe. After wigglers were converted to an even number of poles and adjusted there effect on the pretzeled beam was greatly reduced. The field quality of a number of other magnets was also improved.

Prior to the beginning of the crossing angle machine studies or best performance in 1990 was:

$$\hat{L} = 1.5 \times 10^{32}\ cm^{-2}s^{-1} \tag{1}$$
$$\xi_v = 0.030 \tag{2}$$
$$\hat{I} = 85\ mA/beam \tag{3}$$

At the beginning of 1994, CESR started HEP operation with a crossing angle lattice. In the beginning it was without trains and had 9 bunches per beam. Later after new digital broad band feedback was developed it came smoothly to operation with 18 bunches per beam grouped in 9 trains. Now we have regular operation under this condition with best performance to date as of February 1995 of:

$$\hat{L} = 3.3 \times 10^{32}\ cm^{-2}s^{-1} \tag{4}$$
$$\xi_v = 0.035 \tag{5}$$
$$\hat{I} = 160\ mA/beam \tag{6}$$

During machine study periods we have had successful operation with 9 trains 3 and even 5 bunches per train. We expect that in 1996 we will reach 300 mA/beam and a peak luminosity of $6.0 \times 10^{32}\ cm^{-2}s^{-1}$.

Beam-Beam Performance with a Crossing Angle

The main problem of beam-beam interaction with crossing angle in IP is the following. Let 2θ be a crossing angle. A particle without transfers displacement but with distance S from bunch center will cross the opposite bunch with coordinate θS and will get transverse kick. This kick is proportional opposite bunch density and has nonlinear dependence on S. It gives mechanism for coupling between synchrotron and betatron motion, which introduces synchro-betatron resonances with strength proportional to opposite bunch intensity.

CESR is operating now with ±2.3 milliradian crossing angle at IP. The beam-beam tune shift parameter calculated from luminosity during HEP running 11th April 1995 is shown in figure 3 as function of current per bunch. One can see that the maximum is about 0.036. This good beam-beam performance was arrived at after a several steps. One was a modification of the permanent magnet wigglers [5]. It significantly reduced wigglers nonlinear components. Another step was to turn off several elements with strong nonlinear components of magnetic field. After cleaning up the magnetic lattice the working point was shifted very close to the half integer: Qh=10.52 and Qv=9.63 — a region where there are no principal low order beam-beam resonances. Finally very careful beta function correction and the machine tuning resulted in the beam-beam tune shift parameter reported above.

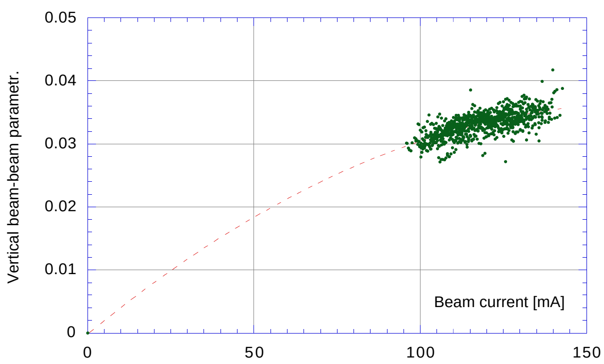

Figure 3: Beam-beam tune shift parameter versus current.

The CESR guide field, as it was mentioned before, includes two 2.5 meter long permanent magnet wigglers for production of intense X-ray beams. The wiggler gap may be varied by remote control. In closed position the peak wiggler's field is 1.2 T. During electron injection the wigglers are opened which lowers the field to about 0.4 T. Just before the beams are collided the wigglers are again closed. Data shown in figure 3 were collected when both wigglers are closed. During machine studies it was found that for both wigglers opened beam-beam tune shift parameter reaches 0.04, *independent of crossing angle for angles less than 2 milliradians.* Thus the nonlinearities of the guide field have so far been more important to the obtainable tune shift parameter than the synchrobetatron coupling introduced by the crossing angle and beam-beam interaction.

Long range Beam-Beam Interaction

One of the most serious problems of multibunch operation is the long range beam-beam interaction at crossings points. The answer to the question of how big the separation should be at each crossing to provide beam stability determines many of the collider's features. This motivated us to carry out an intensive experimental studies. The results of these studies are grouped in two sections. The first one based on [6] describes a linear model of the long range beam-beam interaction and measurements of tune shifts due to parasitic crossings. The second section discuses separation criteria necessary for good lifetime, (see also [7]).

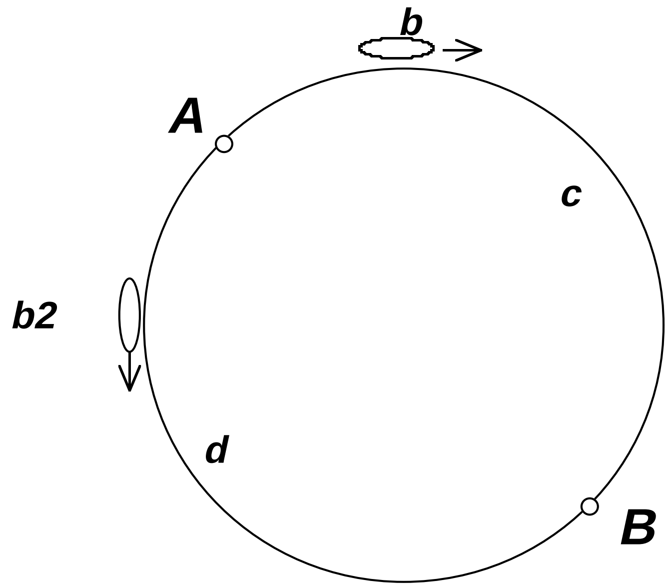

Figure 4: Electrons in bunch b_1 interact with positrons in bunch b_2 at positions **A** and **B**. The phase advance along arc **c** may be different from the phase advance along arc **d**.

Linear Model of the long range beam-beam interaction

Let us assume the separation distances at the crossing points are large compared with the beam sizes. Then the linear approximation of the beam-beam kick angle does not contain significant terms coupling vertical and horizontal motion. Likewise, we assume the linear transport between crossing points does not include coupling and therefore develop only a one dimensional model.

Consider the simplest case of one bunch per beam and refer to figure 4. The electron and positron bunches should interact with each other only at two points **A** and **B** located at the opposite sides of the storage ring. If these points are not on a symmetry axis of the lattice, the betatron phase advance from **A** to **B** on side **c** would not in general be equal to the phase advance on side **d**. This kind of asymmetry leads to some unexpected behavior of coherent modes.

Let us form the vector (X_1, X_1', X_2, X_2'), where $X_{1,(2)}$ and $X_{1,(2)}'$ are the horizontal coordinates and associated angles of bunch $b_{1,(2)}$, appropriately normalized by the horizontal beta function.

The matrix that transports both bunches simultaneously (in opposite directions) through the magnetic structure from **A** to **B** is,

$$M_{A,B} = \begin{pmatrix} \cos\mu_c & \sin\mu_c & 0 & 0 \\ -\sin\mu_c & \cos\mu_c & 0 & 0 \\ 0 & 0 & \cos\mu_d & \sin\mu_d \\ 0 & 0 & -\sin\mu_d & \cos\mu_d \end{pmatrix} \quad (7)$$

where μ_c and μ_d are the absolute values of phase advance from **A** to **B** along side **c** and **d** accordingly. For simplicity we have assumed that magnitude of horizontal beta function is equal to one and its derivative is equal to zero at both points **A** and **B**.

To get the matrix describing the long range beam-beam interaction consider the kick angle produced by the electromagnetic field of b_2 on b_1. If distance between centers of bunches is much larger than the bunch size, then the change of angle will be $\delta X'_1 = 2N_2 r_0/\gamma d$, where N_2 is the number of particles in bunch 2, r_0 the classical electron radius, γ, the Lorentz factor, and d is the distance between bunch centers. Note that d is composed of a closed orbit separation, d_0, and $X_{1,2}$ which are the displacements of bunches $b_{1,2}$ relative to the closed orbit, i.e., $d = d_0 + X_1 - X_2$. Assuming $|X_{1,2}| \ll d_0$ we can rewrite formula for angle change as:

$$\delta X'_1 = \frac{2N_2 r_0}{\gamma d_0} - \frac{2N_2 r_0}{\gamma d_0^2}(X_1 - X_2) \quad (8)$$

Here the first term is a dipole kick, which gives a very small orbit distortion that does not depend on X_1 or X_2. The second term is proportional to bunch displacements. It is like a gradient error and couples the motion of the two beams to produce coherent motion. In what follows, we will ignore the first term and only take into account the gradient term. Conceptually this means we must include the effects of the dipole error as a distortion of the closed orbit. In practice, the distortion of the closed orbit is too small to matter.

The long range beam-beam interaction matrix from just before the kick to just after kick will be

$$M_{int} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 4\pi\delta\nu_1 & 1 & -4\pi\delta\nu_1 & 0 \\ 0 & 0 & 1 & 0 \\ -4\pi\delta\nu_2 & 0 & 4\pi\delta\nu_2 & 1 \end{pmatrix} \quad (9)$$

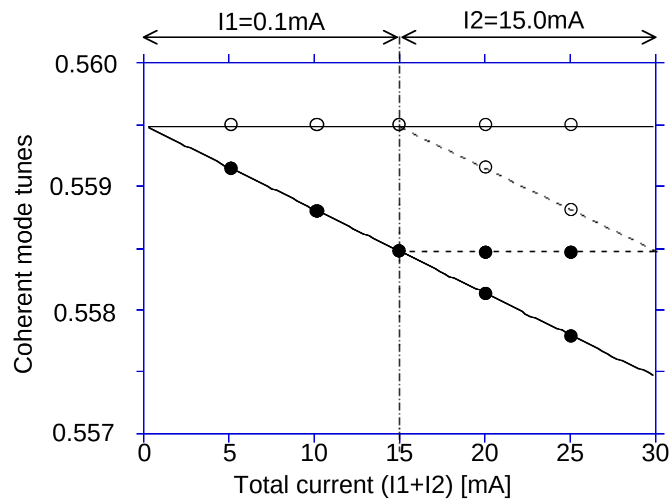

Figure 5: Calculated mode tunes. Open and solid circles refer to the two different modes. Here the effects of asymmetries in the phase advance are evident. Dashed and continuous lines are for the cases of $|\mu_c - \mu_d| = \pi$ or 0. The calculation was done for $\gamma = 10^4$, $d = 29$ mm, $\beta = 40$ m, $N_b = 1.6 \times 10^{11} \times I$ $[mA]$.

where $\delta\nu_{1,2} = N_{2,1} r_0 \beta / 2\pi\gamma d^2$ is the tune shift for a single crossing point and $N_{2,1}$ is the number of particles in bunch 2,1. To get a single turn matrix M_{tot} we must make a matrix multiplication:

$$M_{tot} = M_{int} M_{B,A} M_{int} M_{A,B} \quad (10)$$

where $M_{B,A}$ describes the bunch motion from **B** to **A**. Eigenvalues and eigenvectors of M_{tot} characterize the coherent modes.

In figure 5 we present results of numerical calculation of beam-beam coherent modes as described above. We can see that at low total current, where one bunch is very weak, the tune of the higher frequency mode doesn't depend on bunch intensity, but the lower tune goes down with increasing bunch current. The resulting tune split is proportional to bunch intensity. This picture has a simple interpretation. The unaffected tune belongs to the strong bunch, while the decreasing tune is associated with the motion of the weak bunch. The fact that the tune is decreasing means there is a defocussing effect by large bunch. The tune shift or tune split, both are the same in this case, is the sum of the tune shifts calculated for each of the single crossing points, i.e., $2\delta\nu_1$. An asymmetry in phase advance between **c** and **d** does not matter.

A different situation arises in the case where both bunches have significant intensity. Here the asymmetry in phase advance $\mu_{as} = |\mu_c - \mu_d|$ plays an important role. In figure 5 we see that if the phase advance is zero, i.e., ($\mu_{as} = 0$), the dependence of mode tunes resembles that of the strong-weak case. The tune shift of the lower mode is proportional to sum of bunch intensities and tune split equals to sum of tune shifts at both crossing points. However, if $\mu_{as} = \pi/2$, the higher tune goes down with increasing bunch intensities, while the lower tune remains constant. At the point where the bunch intensities become equal one to another, both coherent beam-beam modes have the same tune shift, which is equal one half the tune split in the $\mu_{as} = 0$ case. Moreover *the tune split equals zero in spite of beam-beam interaction.*

To get a more realistic model which can be compared with experimental data, the beam-wall coherent tune shift and multiple bunches must be taken into account. The beam-wall coherent tune shift should be introduced as an extra phase advance $\delta\mu_{b-w}$ for each bunch. The magnitude of $\delta\mu_{b-w}$ is proportional to bunch intensity and is taken from single beam measurements. To describe a configuration with k bunches per beam, the eigenvalues of matrices of order $2k$ must be evaluated.

Measurements of the long range tune shift

Machine studies were carried out at CESR to measure the long range tune shifts under different conditions as a function of beam current. The choice of bunches and the pretzel configuration insured that there were no head-on collisions at the normal interaction points. Betatron tune shifts were measured on a spectrum analyzer connected to beam pickup electrodes. For an accurate measurement of the frequency it was necessary to artificially spread the tunes of the two beam enough that the peaks would not overlap. This was done by varying sextupole strengths in the region of separated orbits. The betatron resonance widths were about 1 kHz wide which is larger than many of the tune shifts. Signal averaging and careful attention to the frequency measurement were paid – not always successfully – resulting in a variance of the frequency shift measurements of order 0.1 kHz. The optics used were the same as those used during normal operation of CESR.

Bunch		ν_x $\left[\frac{Hz}{mA}\right]$		ν_y $\left[\frac{Hz}{mA}\right]$		pretzel
e^+	e^-	data	theory	data	theory	
1	5	-6 ± 2	-16.4	60 ± 2	66.3	1200
1	5	-42 ± 5	-36.9	183 ± 3	149	800

Table 1: Predicted versus measured long range beam-beam tune shifts.

One of the measurements consisted of one bunch of positrons circulating against one bunch of electrons. The electron bunch was used as a 'probe' beam. Its betatron tunes were measured and its current held constant at 2 mA/bunch while the positron bunch current was reduced from 12 mA to 2 mA. One of the nicer features of this technique is that there is no confusion introduced by frequency shifts due to impedance as the measured beam is held at constant current. Data was taken at two different pretzel amplitudes.

The results are presented on figure 6 and given in the table 1 in comparison with theoretical calculation:

In conclusion one can say the use of tune splits of coherent beam-beam modes to test parasitic interaction points, analogous to the use of $\pi - mode$ and $\sigma - mode$ for head-on collisions may lead to confusing results. Under certain conditions the tune split may be reduced, moreover it may be zero in spite of a strong beam-beam interaction. The best way to study the tune shifts due to the long range beam-beam interaction is to use one bunch per beam and measure the dependence of the coherent tunes on the intensity of one of the bunches keeping the intensity of the other bunch fixed and quite small. Only in this case can you be sure that the tune shift of smallest bunch will be equal to sum of tune shifts for the single interaction points.

Separation Criteria

We have conducted fairly extensive experiments at CESR to measure the minimum separation possible for adequate beam lifetime using a variety of different lattices, crossing points, beam currents, and energies. In all cases we found that if the

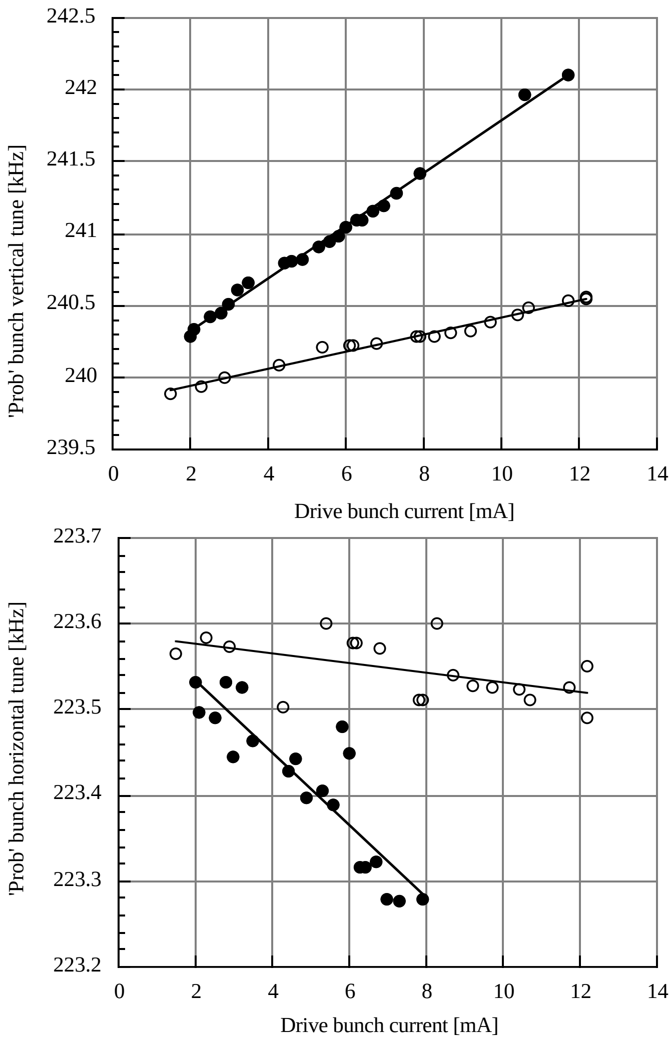

Figure 6: Vertical and horizontal tunes of the 'probe' bunch versus drive bunch current. Open circles refer to the 1200 [c.u.] pretzel. Solid ones are for 800 [c.u.] pretzel.

opposing beam current is large enough, we can adequately fit the minimum separation to a function proportional to the square root of the opposing beam current. However, if the opposing beam current is instead quite small, reasonable lifetime may be obtained with no separation at all. Tracking simulations give similar results. We also found that the minimum required separation depends significantly on the beta functions at the crossing points. A number of phenomenological models/criteria have been evaluated against the experimental data, see [7]. Some of them used have been used to design optics and are discussed here.

Experiments

The basic technique used to study the long range interaction was to fill selected noncolliding bunches and reduce the separation at the crossing points until a poor ($\approx$ 50 minutes) lifetime was observed. The value of the separation obtained represents the minimum necessary (but not sufficient) for acceptable lifetime. Almost always, a small $\approx 10\%$ increase in the separation above the measured minimum was sufficient to obtain very long lifetimes.

In most tests, only one bunch from each beam was filled. In these cases the effects of the long range beam-beam interactions at *two* crossing points are combined. In general, the separation distances, beam sizes, beta functions, etc., were different at the two crossing points, though often the effects from one crossing point dominated. In other tests, one bunch was filled against two or three noncolliding bunches in the opposite beam. For each test, only the overall separation amplitude was adjusted so the individual separation distances at the different crossing points were changed proportionally.

Four completely different lattices were used for the experiments, with varying beta functions, tunes, sextupole distributions, emittances and in the case of optics D of table 2, slightly different energy. We tested several crossing points by filling different combinations of bunches. Note the rather broad range of maximum tune shift parameters (0.00082 to 0.00357) and a rather narrower range of B parameters (0.089 to 0.146).

Set	Optics	$\delta\nu_{max}$	B
1	A	2.44×10^{-3}	14.6 ± 0.7
2	A	1.76×10^{-3}	13.4 ± 0.5
3	B	1.00×10^{-3}	8.9 ± 1.7
4	C	0.86×10^{-3}	9.3 ± 0.1
5	C	1.12×10^{-3}	9.3 ± 0.9
6	C	1.30×10^{-3}	9.8 ± 0.4
7	C	0.82×10^{-3}	10.0 ± 0.6
8	D	1.43×10^{-3}	14.1 ± 2.9
9	C	3.57×10^{-3}	13.3 ± 0.3
10	C	2.11×10^{-3}	13.0 ± 3.2
11	C	1.86×10^{-3}	14.0 ± 2.4
12	C	3.57×10^{-3}	10.5 ± 0.4

Table 2: Various set of crossing points for four different lattices experimentally yield a range of maximum long range tune shift parameters and B parameters at the minimum limiting pretzel amplitude. B parameter definition see below.

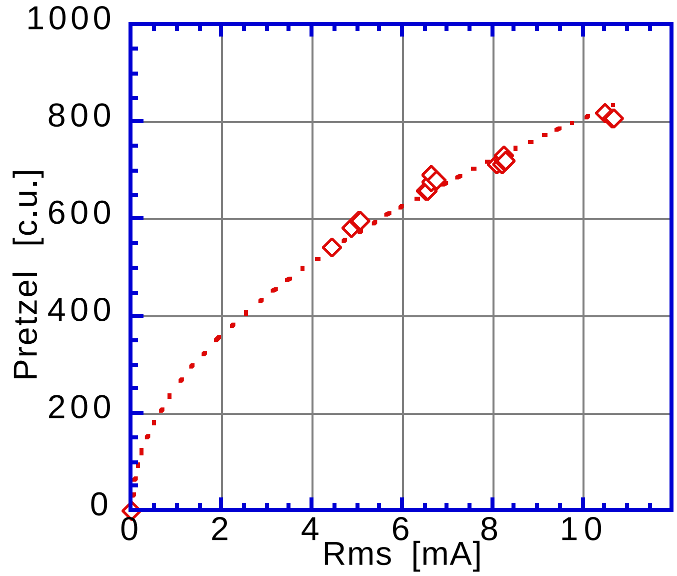

Figure 7: The minimum separation amplitude obtained for different opposing beam currents is plotted. 1000 units of separation corresponds roughly to a typical maximum separation of ± 10 mm. In this case one bunch in each beam is colliding at two points with optical properties defined in table 2 row 1.

For each configuration, the minimum separation was measured over a range of opposing beam currents. An example of the current dependence of the minimum required separation is given in figure 7. A best fit curve, assuming the minimum separation is proportional to the square root of the current, is superposed on the plot. This choice of fitting does a somewhat better job than a simple linear fitting when applied to all the data, though in this case the difference is small. It does not fit well if the current is reduced to the point where it is possible to obtain head-on collisions, but such currents are generally less than the design currents.

Phenomenology

In the previous section it was mentioned that square root fitting of minimum separation as function of current does a good job for all experimental data sets if current is big enough. This fact motivated us to check out the separation criteria based on assumption that long range tune shift per crossing point is fundamental limit. Column 3 in table 2 named $\delta\nu_{max}$ shows the maximum long range tune shift among parasitic crossings calculated from square root fitting for various data sets.

In some cases the maximum of residual tune shift is in vertical direction and some times it is in horizontal plane. It depends on ration between β_v and β_h and probably η. By itself, with this criterion can expect large uncertainty in the prediction of required separation for good lifetime.

The experimental results of another approach are in column 4 of table 2. Using the B parameter described below, we have a much more reliable predictor of the required separation.

The definition of B is motivated by the following observations:

- Minimum separation is roughly proportional square root of current. So expect combinations like I_b/d^2.
- Primitive tracking shows that instabilities are happening in vertical direction. This motivated us put β_v into parameter in combination with current as $I_b\beta_v$.
- The criterion should contain beam size σ_x because for bigger σ_x and a given separation more particles pass close to opposite beam making situation worse.
- The resulting interaction caused instability must incorporate interactions from each para-

sitic crossing in an effectively incoherent way. So, we can assume that criteria should have construction like $\sqrt{\sum_i^{N_{cp}}(I_b...)_i^2}$. Where N_{cp} is number of crossing points and I_b is current per bunch.

All above assumptions collected together give us criterion in form:

$$B = I_b\sqrt{\sum_i^{N_{cp}}(\frac{\beta_v\sigma_x^2}{d^2})_i^2} \qquad (11)$$

Table 2 shows the value of B for 12 data sets for different kind of optics, where various $\beta_{x,y}$ and η function and for different number of parasitic crossings were used. Numerical value of B were calculated for $\beta_{h,v}$ in m, σ_x and d in mm, bunch current in mA. One can see that the spread of B parameter value among experimental data sets, $B = 11.7 \pm 2.2$, is much smaller than it is for $\delta\nu_{max}$, $\delta\nu_{max} = (1.82 \pm 0.96) \times 10^{-3}$.

Really three criteria relating to long range beam-beam interaction were included in process of crossing angle optic design [9]. The first was that separation between opposite beam orbit at crossing points should be bigger than $10\sigma_x$. The second request was that residual long range tune shift due to interaction in each crossing should be less than 1.0×10^{-3}. The last criterion was to minimize B. The substantial difference between the two first constraints and the last criteria is that only the B parameter criteria has a direct dependence on the number of parasitic crossings.

Note that B parameter is not dimensionless and it is not clear its physical interpretation. In addition we do not know any data from other facilities to check out how it works on them.

Conclusions

In conclusion let us say that CESR has been running quite successfully for over a year with crossing angles. This has resulting in a new record luminosity. The experience gained in implementing crossing angles has shown that so far the pretzel effects are more important than the beam-beam synchrobetatron coupling introduced. Finally, numerous experiments studying the effects of the long range beam-beam interaction have given us sufficient understanding to be able to design lattice where the effects are minimized.

Acknowledgments

Much of the work reported in this paper, especially the beam-beam performance with a crossing angle was done by D. Rubin. He also was responsible for overall optics design and led the machine studies effort which resulted in the successful implementation of crossing angles. We would also like to acknowledge the rest of the CESR operations group for their support.

References

[1] David Rice for CESR Operations Group. *CESR Luminosity Upgrades and Experiments*, -In proc. PAC 93, p.1978.

[2] David Rice for CESR Operations Group. *High Luminosity Operation of the Cornell Electron storage Ring*, -In proc. PAC 89, p.444.

[3] R.E. Meller *Proposal for CESR Mini-B*, CESR Operation Note CON 90-17 (1990).

[4] A. Piwinski, 1977 Particle Accelerator Conference., IEEE Trans. on Nuclear Science, NS-24, No.3, 1408 (1977).

[5] D. Frachon, I. Vasserman, J Welch and A. Temnykh *Magnetic Measurements of the West Wiggler in CESR*, CBN 93 - 7, Cornell 1993.

[6] A. B. Temnykh and J. J. Welch, *Some Aspects of the Long Range Beam-Beam Interaction in Storage Ring*, - In: Proc of PAC 93, Washington, D.C., May 17-20, (1993), CBN 92-13, Nov. 1992.

[7] A. B. Temnykh, J. J. Welch and D. H. Rice, *The Long Range Beam-Beam Interaction at CESR - Experiments, Simulation and Phenomenology*, - In: Proc of PAC 93, Washington, D.C., May 17-20, (1993)

[8] D. Rice, *et. al. Symmetric Beam-Beam Experience* CBN 92-10 Cornell U., proc. SLAC B Factory Workshop, April 1992

[9] D. Rubin, *et. al. CESR Upgrade* , - In: Proc of PAC 95, Dallas, May 1-5, (1995)