The Long Range Beam-Beam Interaction at CESR — Experiments, Simulation and Phenomenology *

Alexander B. Temnykh†, James J. Welch and David H. Rice, Wilson Lab, Cornell U., Ithaca NY

Introduction

A direct route to higher luminosity at colliding beam storage rings is to increase the average beam current by increasing the number of bunches in each beam. However, as the number of bunches increases, so does the number of crossing points where bunches from opposing beams may interact destructively. The most obvious result of these long range interactions, (often seen at CESR), is poor beam lifetime. An increasingly important issue is then how to determine the minimum separation required for adequate lifetime [2] [3]. We have conducted fairly extensive experiments at CESR to measure the minimum separation using a variety of different optics, crossing points, beam currents, and energies. In all cases we found that if the 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 suitable for use in designing optics have been evaluated against the experimental data and the results are reported here. Some traditional models did not fare well in this evaluation.

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 1, slightly different energy. We tested several crossing points by filling different combinations of bunches. The theoretical values of the optical functions for each of the one on one bunch configurations used in the tests are given in table 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 1. 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.

Simulation

We simulated some of the experimental data by tracking using the BEAMBEAM element in the MAD program [1]. Sextupoles were included and betatron and synchrotron tunes were adjusted to the measured values.

Lifetime is not simulated directly. Instead the tracking efforts were aimed at finding out what kinds of dynamics come into play when the long range interaction becomes strong. To make sure that all kinds of modulation were excited we used initial amplitudes in all three dimensions: vertical, horizontal and synchrotron, and used four particles with different initial synchrotron phases. Most of the study involved initial amplitudes of 3.2 σ. If there was an aperture at 3.2σ in any dimension, a gaussian beam would have about a 50 minute lifetime. The number of turns

*Work supported by the National Science Foundation
†On leave from BINP, Novisibirsk

0-7803-1203-1/93$03.00 © 1993 IEEE

Table 1: Design values of crossing point optical parameters for each of the test configurations are listed. Subscripts 1,2 refer to crossing points locations on on opposite sides of the ring. The separation distances, s_1, s_2, are the millimeters of separation obtained when the separation amplitude is 1000 units. The horizontal beam size σ_x is in millimeters, while the rest of the betatron functions are given in meters. The relative energy spread δ, is about 6.3×10^{-4} for all lattices.

Set	Optics	β_{x1}	β_{y1}	η_1	σ_{x1}	s_1	β_{x2}	β_{y2}	η_2	σ_{x2}	s_2
1	A	5.9	27.9	1.6	1.6	11.2	8.7	31.4	1.8	1.89	12.0
2	A	13.6	16.2	3.0	2.65	17.5	24.9	8.9	2.7	3.05	18.4
3	B	16.0	16.8	2.0	2.19	8.8	14.5	26.9	3.4	2.74	13.4
4	C	18.9	18.2	2.5	2.64	10.9	12.4	19.7	2.3	2.27	10.7
5	C	30.4	10.6	2.8	3.20	16.7	15.1	13.9	3.0	2.66	13.5
6	C	12.9	23.6	2.1	2.21	10.4	9.0	21.2	1.6	1.83	10.9
7	D	19.7	24.0	2.4	2.57	10.4	18.4	18.1	1.6	2.25	15.0
8	C	13.5	87.9	0.0	1.64	7.2	7.3	12.2	0.2	1.21	8.3
9	C	99.7	25.21	0.1	4.47	17.5	35.0	10.3	0.5	2.66	16.8
10	C	12.9	23.6	2.1	2.21	9.20	9.0	21.2	1.6	1.83	10.45
11	C	13.5	87.9	0.0	1.64	7.2	7.3	12.2	0.2	1.21	8.3

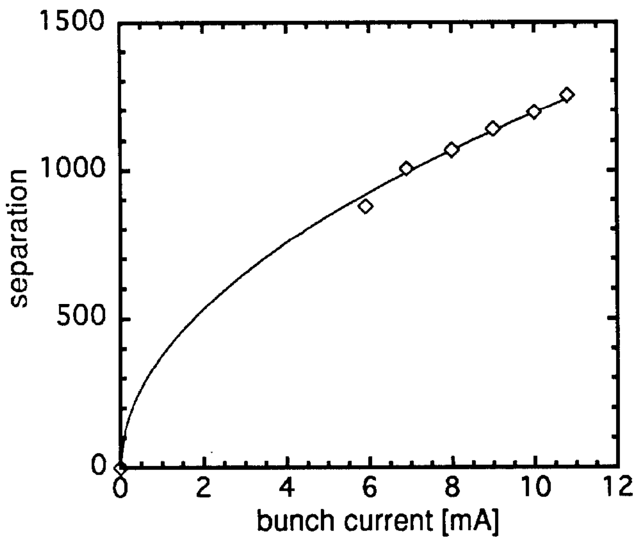

Figure 1: The minimum separation amplitude obtained for different opposing beam currents is plotted. 1000 units of separation corresponds roughly to a typical maximum separation of ±10 mm. In this case one bunch in each beam is colliding at two points with optical properties defined in table 1.

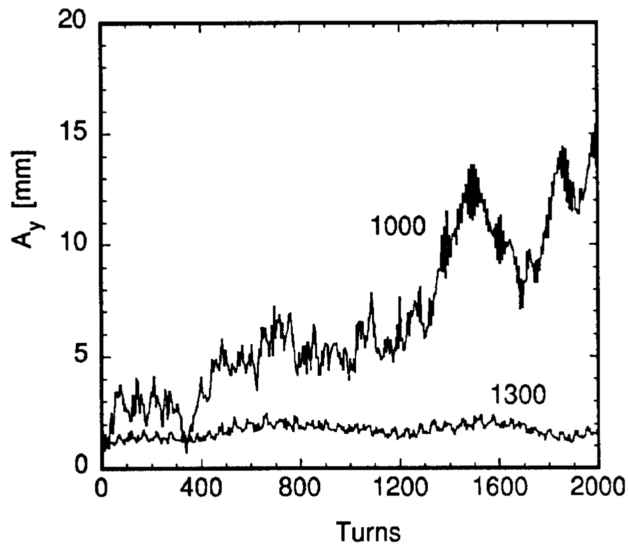

Figure 2: The maximum vertical amplitude of four test particles was tracked for 2000 turns with two different separation amplitudes. At 1300 units of separation the vertical amplitude is stable, while at 1000 units, the amplitude grows rapidly to near the machine aperture.

tracked was 2000 which corresponds to substantially less than the radiation damping time.

In figure 2 we show an example of results of a simulation corresponding to data set 5 in table 1 for an opposing beam current of 10 mA. In particular we plot the vertical amplitude as a function of the turn number. At the larger separation amplitude of 1300 units, tracking gives no discernible growth in vertical amplitude. When the separation is reduced to 1000 units, tracking shows an unstable vertical amplitude and growth rate sufficient to take the average tracked particle out near the vertical physical aperture of the machine. Experimentally we observed that at 1200 units the beam had a 50 minute lifetime, but when the separation was reduced/increased the lifetime rapidly decreased/increased. This comparison was made against several of the machine studies results with similar results.

In the simulations, the horizontal and synchrotron amplitudes never exhibited large instabilities. Only the vertical amplitude seems to be seriously affected by the long range beam beam interaction.

Table 2: The predictive abilities of various phenomenological models, labeled A through K, for determining the minimum separation amplitudes for good lifetime are compared in this table. The models were applied to experimental results obtained from 11 different configurations of crossing points and lattices. In this table X_i refers to the distance in millimeters between beam centerlines at crossing point i, and ξ_i is the long range tune shift parameter. The free parameters n_σ, C, and C' are adjusted for best-fit.

	DESCRIPTION	BEST FIT at 10 mA	RMS
A	$X_i \geq n_\sigma \sigma_{xi} + C\sqrt{\beta_{xi}\beta_{yi}}$	$n_\sigma = 2.0$ $C = .31$	0.124
B	$X_i \geq n_\sigma \sigma_{xi}$	$n_\sigma = 4.5$	0.255
C	$X_i \geq C$	$C = 11.0$	0.203
D	$\xi_i \leq C$, x or y	$C = 0.0019$	0.212
E	$\sum \beta_{yi}\sigma_i^2/X_i^2 \leq C$	$C = 1.61$	0.112
F	$X_i \geq C + n_\sigma \sigma_{xi}$	$C = 7.4$ $n_\sigma = 1.6$	0.190
G	$X_i \geq C + C'\sigma_{xi}\sqrt{\beta_{yi}}$	$C = 2.75$ $C' = 0.73$	0.120
H	$\sqrt{\sum \xi_i^2} \leq C$	$C = 0.0021$	0.192
I	$X_i \geq n_\sigma \sigma_{\beta xi}$	$n_\sigma = 5.50$	0.227
J	$X_i \geq C + C'/\sigma_{xi}$	$C = 11$ $C' = 0.0$	0.203
K	$\sum \beta_{yi}^2 \sigma i^4/X_i^4 \leq C$	$C = 3.00$	0.144

Phenomenology

A number of phenomenological models describing separation criteria for good lifetime were constructed. They were checked against the results of the machine experiments for a beam current of 10 mA. Only the one-on-one bunch data were used in this comparison and the results are shown in table 2. All models implicitly assume the tunes were adjusted to get away from destructive resonances, as was done in the experiment.

The models are compared on the basis of the root mean square deviation of the predicted minimum separation amplitude from the actual obtained in machine studies, normalized to the actual separation amplitude. All models assume either one or two free parameters which were varied to obtain the minimum RMS. The best performing of the models, E, gives a best-fit RMS of .11 (11%), which is about as well as we can expect given the limited accuracy with which we know the actual optical functions at the crossing points. The worst of the models give an RMS more than 20%.

The two-parameter models seek to describe the data by requiring the separation at all crossing points be greater than an amount which depends on an effective core size and the distance between the test beam and the core edge. This is motivated by the rapid increase in the vertical beam-beam deflection for particles which pass close to the center of the opposing beam [4]. The best performing "variable core" models, A and G, require greater separation at points with larger β_y and larger σ_x. The worst performing core models, F and J, do not have any β_y dependence.

The one-parameter models are of two types. Models E, J and K add up the effects from all crossing points, while the other one-parameter models simply require that the separation distance at all crossing points be greater than some model dependent number. Model E gives more weight to points with high β_y and large beam sizes.

Two models previously used extensively in design criteria at CESR are D and I. Model D requires all long range tune shift parameters be less than a fixed value, and model I requires at least some fixed number of betatron sigma between beam centers. These models are among the worst at describing machine performance. In fact they predict a minimum separation amplitude which in some data is in error by a factor of two.

Conclusions

The correlation of the tracking results with machine studies data is very encouraging. However, such tracking can only be used to check a lattice design, and is too cumbersome to be used in the optimization programs that are used to generate a lattice. In this regard, we are pleased to see that some phenomenological models can give reasonably good prediction of required separation, at least for the range of parameters we have been able to test. Further experimental work will extend the range to include larger and smaller beta functions, and examine more of the effects of multiple bunches per beam. For one-on-one bunch configurations models A, E and B are about equally good. A lattice designer might use any of these for optimization and check the results against tracking. He should keep in mind a small ($\approx$ 10%) increase in separation will be needed to get from the marginal 50 minute lifetime predicted by the models to long lifetimes acceptable for running conditions.

References

[1] MAD — Methodical Accelerator Design, Version 8.1 from CERN

[2] B. Goddard, W. Herr, J. M. Jowett, M. Lamont, *Measurements of minimum pretzel separation as a function of energy*, SL-MD Note 67, Nov 1992

[3] Alexander B. Temnykh, James J. Welch, *Some Aspects of the Long Range Beam-Beam Interaction in Storage Rings*, CBN 92-13, Nov. 1992.

[4] Alexander B. Temnykh *Tune Spread and Tune Shift for the Long Range Beam-Beam Interaction* CBN 93-1, March 1993.