THE INCOHERENT LONG RANGE BEAM-BEAM INTERACTION IN CESR.*

Alexander Temnykh† and David Sagan
Cornell University, Ithaca NY

1 INTRODUCTION

CESR has reached the world's highest luminosity using mutibunch operation. The key to this operation is a horizontal 'pretzel' separation of the beams in the arcs and a crossing angle at the IP. The pretzel separation is needed since the counter rotating bunches share the same beam pipe and there is thus a long range beam–beam interaction (LRBBI) between the beams. The LRBBI involves individual particles of one beam (henceforth called the "probe" beam) interacting with the other "strong" beam. Particles of the probe beam are destabilized when their horizontal oscillation amplitude is large enough to pass near the strong beam. This sets the limit for the minimum practical pretzel separation between beams.

Future plans call for increases in current as well as the number of bunches. Since more current will mean a stronger beam-beam kick and more bunches will mean more parasitic crossing points, it is important to understand how the LRBBI destabilizes particles. Temnykh, Welch and Rice[2] have studied the LRBBI experimentally and have put forward phenomenological models to predict the minimum separation achievable for a 50 minute beam lifetime.

To go beyond these phenomenological models the way in which the LRBBI destabilizes particles must be understood. It is shown in this paper using a simple numerical simulation that, with CESR (Cornell Electron/positron Stroage Ring) conditions, and with the beams separated horizontally, the LRBBI leads to vertical beam tail growth and loss of particles in the vertical plane. Furthermore, the threshold of this instability depends on the vertical size of the opposite beam. An increase of the vertical size of the opposite beam leads to an increase of the allowed beam intensity for a given separation and for a given lifetime. These conclusions are shown to be supported experimentally.

2 TRACKING

Using a tracking simulation a previous study[2] found that the horizontal and synchrotron motion did not exhibit instabilities. Only the vertical motion was seriously affected by the LRBBI. At the time it was not clear why this was so. A simple explanation for this can be constructed as follows: Consider a simple particle tracking model where a particle is first transformed from a parasitic collision point back to the parasitic collision point using a linear matrix. After the 'arc' transport the LRBBI kick is given by

Parameter	Symbol	value
Horizontal beta	β_x	10 m
Vertical beta	β_y	20 m
Horizontal tune	Q_x	0.538
Vertical tune	Q_y	0.602
Horizontal sigma	σ_x	1.50 mm
Vertical sigma	σ_y	0.25 mm
Bunch-bunch offset	x_{sep}	9.3 mm
Strong bunch current	I	10.0 mA

Table 1: Parameters used in tracking.

$$(x', y') = (\mathcal{F}_x(x - x_{sep}, y), \mathcal{F}_y(x - x_{sep}, y)) \quad (1)$$

where the kick $\mathcal{F}$ is calculated from the standard Bassetti and Erskine formula[3] for a bi–Gaussian strong bunch and x_{sep} is the horizontal separation of the beams.

Figure 1 shows the results of tracking using parameters appropriate for minimum acceptable separation in CESR as given in table 1. The beams were separated by a distance $x_{sep} = 9.3\,\text{mm}$ $(6.3\sigma_x)$ the tracked partical had initially $x = 5.5\sigma_x$ (corresponding to a 50 min lifetime) and $y = 1.0\sigma_y$. The particle was tracked for 1000 turns. As seen in the figure, the horizontal motion is stable and practically unperturbed. The vertical motion, on the other hand, looks chaotic. This simple simulation agrees well with previous results[2].

The vertical kick is strongly influenced by the horizontal oscillations. This coupling from horizontal to vertical makes the analysis of the vertical motion extremely complicated. With this being said, in order to try to understand the vertical motion consider the following numerical experiment: Consider the motion of a particle in vertical phase space due to the LRBBI assuming that the x–position of the particle is frozen at some constant value. For purposes of illustration consider the particle tracked in figure 1. On the first turn it had $x_{\text{off}} \equiv x - x_{sep} = 0.86\,\sigma_x$, on the second turn x_{off} was $9.90\,\sigma_x$. The vertical phase space with x_{off} fixed at these two values is shown in figures 2a and 2b respectively. With $x_{\text{off}} = 0.86\sigma_x$ the difference in vertical tune between small and large amplitudes is large enough such that two low order nonlinear resonances can be excited. Overlapping of these resonances results in the appearance of a stochastic region up to $15\sigma_y$. In this region there is strong diffusion and particles experience fast and unpredictable changes in amplitude. In figure 2*b* there are stable, practically unperturbed, trajectories.

If we now include the effect of the horizontal motion we see that a particle passes near the center of the opposite

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† On leave from BINP, Novisibirsk

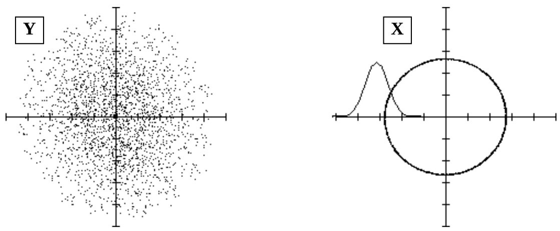

Figure 1: Tracking simulation in phase space using the parameters of table 1. The starting point was $(x, x', y, y') = (5.5\sigma_x, 01.0\sigma_y, 0)$ The scale is $2\sigma_{x,y}$ per division. The Gaussian curve in the X plot is the horizontal strong bunch profile.

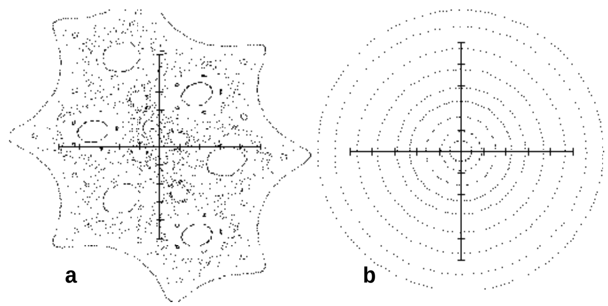

Figure 2: Vertical phase space for particles with fixed $x_{\text{off}} = x - x_{sep}$. (a) $x_{\text{off}} = 0.86\sigma_x$, (b) $x_{\text{off}} = 9.90\sigma_x$.

beam, due to the stochastic motion seen on figure $2a$ the vertical amplitude will be unpredictably changed. This will cause diffusion in vertical phase space as has been seen in figure 1. The condition for resonances overlapping, seen on figure $2a$, is affected by the vertical strong beam size and by the strong beam intensity. An increase of the vertical beam size for a given intensity reduces the strength of the resonance harmonics as well as the tune difference between large and small amplitude. This results in a reduction of the number of resonances between these amplitudes and the disappearance of the stochastic region. This will stabilize the vertical motion.

Figures 3 and 4 illustrate this. Figure 3 shows the vertical motion using the same parameters as used for figure $2a$ except with a strong beam vertical size of $\sigma_y = 0.75$ mm which is 3 times larger than what was used for figure $2a$. The figure shows regular trajectories with little sign of chaotic behavior. Figure 4 shows the 2 dimensional tracking and in contrast with figure 1 there is no hint of unstable motion. Thus, with an increase in vertical beam size we can expect that for a given separation it should be possible to reach higher beam current. This is indeed seen experimentally as discussed in the next section.

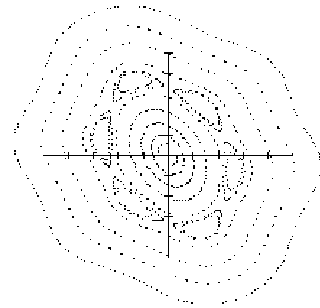

Figure 3: Vertical phase space for particles with the same the same conditions as in figure $2a$ except with a large strong beam sige of $\sigma_y = 0.75$ mm.

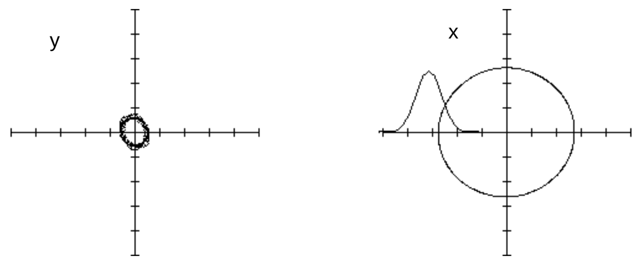

Figure 4: Tracking with a large strong beam size of $\sigma_y = 0.75\,mm$. Other parameters same as used in figure 1.

3 EXPERIMENTS AT CESR

The enlargement of the beam tails due to the LRBBI was measured experimentally by by monitoring beam lifetime versus the position of a scraper. One bunch per each beam were filled that the bunches did not collide at the IP but interacted at two opposing parasitic crossing points in the arcs. Table 2 gives parameters of the two crossing points.

Figures 5 and 6 show the loss rates (which in the tails are roughly proportional to the beam density at the scrapper tip) for horizontal and vertical scrapping as a function of scraper position with and without the strong bunch. For the horizontal, the presence of the strong bunch only enlarged the tails by 20% or so. For the vertical the enlargement of the tails was dramatic such that the size of the vertical tails became similar to that of the horizontal. This is in qualitative agreement with tracking and shows that the instability is indeed a vertical one.

Parameter	PC1	PC2
$\beta_x(m)$	9.30	10.30
$\beta_y(m)$	33.20	20.40
$\eta(m)$	0.10	1.19
$\sigma_x(mm)$	1.26	1.51
$x_{sep}(mm)$	9.16	9.78
x_{sep}/σ_x	7.26	6.47

Table 2: Parameters at the parasitic crossing points.

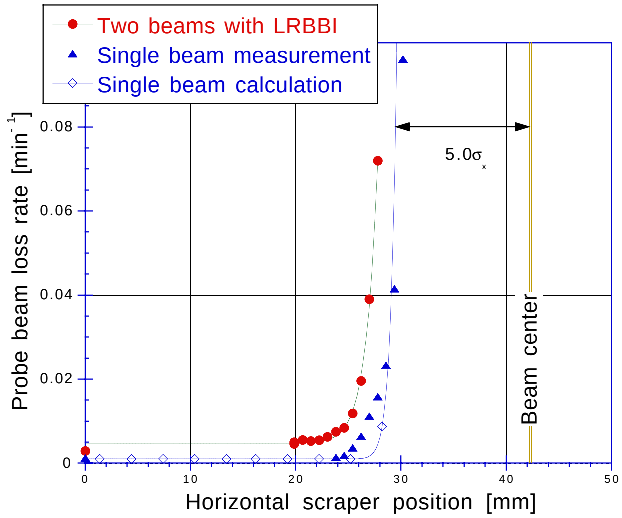

Figure 5: Weak beam loss rate versus horizontal scraper position.

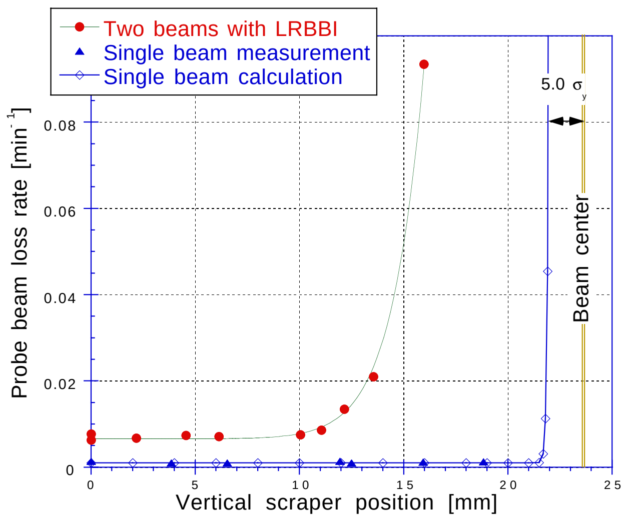

Figure 6: Weak beam loss rate versus vertical scraper position.

To observe the effect of vertical strong beam size on the LRBBI, experiments were preformed where the lifetime of a probe bunch was measured as a function of current for fixed vertical strong beam size. The vertical beam size of the strong bunch was varied without affecting the probe bunch by taking advantage of the fact that the beams follow different trajectories. It was thus possible to change the tune of one beam but not the other by using sextupole magnets. By tuning the strong bunch to be near the coupling resonance sideband $Q_x - Q_y + Q_s = n$ the strong bunch beam size could be increased without affecting the probe bunch. The conditions here are the same at with the first experiment.

The probe positron bunch had a current of 3 to 5 mA while the strong electron bunch had currents up to 18 mA. Care was taken to keep beam tunes, beam-beam separation,

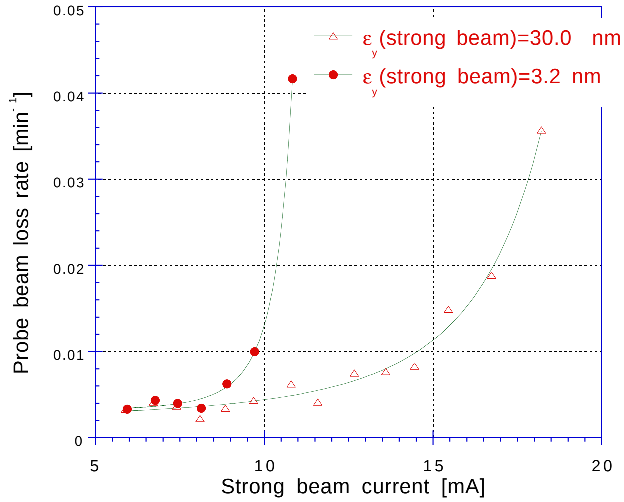

Figure 7: Probe beam loss rate versus strong beam current.

etc. constant. In particular the horizontal emittance of the strong beam was constant in spite of the presence of the coupling sideband resonance used to vary the vertical beam size.

Figure 7 shows the probe beam loss rate for two different strong beam sizes. As can be seen from the figure the loss rate of the probe beam is very dependent on the strong vertical size with the larger stron beam size giving a dramatically lower loss rate.

4 CONCLUSIONS

We have found good qualitative agreement between a simple simulation model and experiment which indicates that the incoherent LRBBI may be simply simulated with good reliability. In particular it is shown that there is diffusion in the vertical plane. It is also seen that a larger vertical beam size decreases the LRBBI which. This fact could possibly be used to achieve smaller separations at the parasitic crossing points.

5 ACKNOWLEDGMENTS

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6 REFERENCES

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[3] M. Bassetti and G. Erskine, CERN-ISR-TH/80–06 (1970).