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# Simulation of the Beam Current Limitation Due to Long Range Beam-Beam Interaction in CESR

Edward Pozdeev * and Alexander Temnykh

Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853, USA

**Abstract**

The simulation of the beam current limitation due to Long Range Beam-Beam Interaction (LRBBI) for CESR was performed by tracking using program MAD [13]. MAD-input file has been prepared by Z2MAD code [10]. The input file included BEAM-BEAM elements at parasitic crossing points to simulate LRBBI and all known nonlinearities of the CESR elements. Comparing the simple experiment data with tracking we evaluated criteria allowing us to extrapolate tracking results to experiments. Applying this criteria to tracking for CESR Phase II and CESR Phase III we found a beam current limitation for this optics.

## 1 Introduction

Cornell Electron Storage Ring (CESR) is single ring electron-positron collider operating in muti-bunch mode. In the present, each counter-rotating beam contains 18 bunches and in near future the number of bunches will be increased up to 45 per beam. As the both beams share the same vacuum pipe there is interaction between them at parasitic crossings (PC) where counter-rotating bunches pass each other. To reduce the strength of this interaction there is horizontal “pretzel” separation between counter-rotating beams. In fact, the ”pretzel” is a closed orbit distortion created by four electrostatic separators with maximums around PCs location. At CESR ”pretzel” provides separation between beams at PCs in range of $5 \div 9\sigma_x$, where $\sigma_x$ is horizontal beam size. Despite the strength of interaction is significantly reduced it still strong enough to disturb beam dynamics. In literature interaction between well separated beams is called Long Range Beam-Beam Interaction (LRBBI). This problem was intensively studied at CESR, see references [5]-[8], as well as around the world, see [1]-[4].

The reported work continues the CESR nonlinear beam dynamic study, see [11], using program MAD. In the previous work the MAD-input file contained all known up to date CESR magnetic elements nonlinearities was used to simulate experimental observations for single beam. A good agreement was found between measured and calculated dependence of betatron tunes on beam orbit distortion. Furthermore, real betatron tune scans, i.e., completed on CESR, and scans simulated by tracking with MAD showed the same set of excited nonlinear resonances. A new software developed by Pozdeev, see [10], allowed to include a set of beam-beam elements at PCs location into MAD-input file in addition to nonlinearities of magnetic elements . Using this file we were able to simulate LRBBI limit for variety of CESR configurations.

## 2 Tracking procedure optimization

In the previous works [6], [8] it has been shown that long range beam-beam interaction affects vertical motion of particles with large horizontal amplitudes, i.e., particles appearing in horizontal

*On leave from BINP, Novosibirsk

tails close to the opposite beam, and practically it does not affect horizontal and synchrotron motion. The vertical instability leads to loss of these particles, resulting in beam life time decrease. For it does not matter what kind of motion bring these particles close to opposite beam, i.e., synchrotron motion combined with dispersion or betatron oscillation, in future only betatron motion in horizontal plane will be modeled.

To select optimal initial conditions for future tracking, in the beginning we modeled the single parasitic interaction. We used CESR optics N9A19C501.FD93S_4S converted into MAD-input file by program $Z2MAD$ described in [10]. This file included all known nonlinearities and the closed orbit distortion,"pretzel", used to separate counter-rotating beams. One single BEAM-BEAM element was added to represent a parasitic interaction. Tracking was then performed for various numbers of turns and for different initial horizontal and vertical amplitudes. Results are plotted on figure 1. Here is the maximum of vertical amplitude reached by particles of probe beam during tracking as a function of initial horizontal displacement. Plots show results of 2500, 500 and 50 turns tracking, for $0\sigma_z$,$1\sigma_z$ and $2\sigma_z$ initial vertical amplitude.

It can be seen that there is no sign of vertical amplitude increase for particles with small horizontal amplitudes, i.e., for particles that pass the opposite beam at the distance larger than $5\,mm(5\sigma_x)$. Particles with horizontal amplitude bigger than $6\,mm$, i.e., particles passing opposite beam closer than $4\,mm$ $(4\sigma_x)$, show strong vertical motion instability. Hereafter, the horizontal amplitude at which vertical instability starts to appear will be referred to as the critical amplitude. Comparing $0\sigma_z$,$1\sigma_z$ and $2\sigma_z$ curves one can see that this amplitude as well as the maximum vertical displacement does not depend on the initial vertical coordinate. To avoid confusion it should be noticed that due to tiny vertical separation $y_s$ at the PC, see caption on figure 1, even in the case of zero for initial vertical displacement, the vertical kick is being generated by LRBBI. It results in small vertical oscillations which become unstable if horizontal amplitude is larger than critical. Since the difference in initial vertical position does not effect the final results, we will start all our tracking with zero for initial vertical displacement.

Let's consider the number of turns we have to track particles for. Because we would like to have minimal tracking time the number of turns should be as small as possible. However, it should be big enough not to miss any important effect. Let's compare tracking for 50, 500 and 2500 turns shown on figure 1. Here, one can see that the critical horizontal amplitude practically does not depend on number of turns. The maximum vertical displacement reached by particles is around $0.006mm$ for 50 turns tracking, $0.014mm$ for 500 turns and $0.016mm$ for 2500 turns. There is a large factor of 2.3 between 50 and 500 turns and only 0.1 between 500 and 2500 turns. The latter assures us that the maximum amplitude obtained by particles in 2500 turns tracking will not differ much from amplitudes for 10000 turns tracking, when radiation damping[†] starts to stabilize the particles motion. Based on this we decided use 2500 turns for tracking.

# 3 Two parasitic crossing points experiment and simulation

To test our tracking model we simulated the following simple experiment devoted to study LRBBI at CESR, see MS elog, Jan 16 1996. In this experiment, two counter-rotating bunches, a probe positron bunch of $2mA$, and strong electron bunch with varying intensity, have been filled. They were interacting in two parasitic points at the opposite side of ring as is shown in figure 2. Parameters of these PCs are given in figure 2. Then the minimum separation required for $30\,min$ life time of the probe bunch as a function of strong bunch intensity was determined. It is plotted by solid points and approximated by line on figure 3.

[†]Vertical radiation damping time at CESR is approximately 10000 turns

To reproduce experimental conditions in tracking, CESR's optics N9A19C501.FD93S_4S being used at that moment was converted into MAD-input file and all known nonlinear components were added. The file "csr_set.36735" described CESR's conditions at the moment of measurements was used to calculate sextupole distribution, nonlinearities generated by vertical steering magnets and by electrostatic horizontal separators. Collimators with dimensions of the beam pipe were added to the MAD-input file to simulate mechanical aperture. Two BEAM-BEAM elements were placed at parasitic crossing points locations, see figure 2, to simulate LRBBI. Particles were started with zero vertical displacement and were tracked for 2500 turns. For given beam intensity and for given horizontal amplitude there is a minimum pretzel which allows survival of probe particles for all tracking time. If the pretzel is less then this minimum then tracking particles are driven by LRBBI to large vertical amplitudes and are being lost due to exceeding the aperture defined by collimators. Note that the loss particles indicates beam life time degradation. Four plots on figure 3 show this minimum pretzel obtained by tracking as a function of beam intensity for different horizontal amplitudes of probe particles, ($5.0\sigma_x$, $5.5\sigma_x$, $6\sigma_x$ and $6.5\sigma_x$).

Comparing data on figure 3 one can see that the nearly all experimental points are between plots corresponding to $5.5\sigma_x$ and $6\sigma_x$ particle lost. In fact, it is a very reasonable. Let's calculate quantum beam life time due to aperture limitation at $5.5\sigma_x$ and $6.0\sigma_x$, i.e., due to particles lost at these amplitudes. Using formula from [12]:

$$\tau_q = \frac{\tau_x}{A^2} \exp\left(\frac{A^2}{2}\right)$$

where $\tau_q$ quantum beam life time, $A$ is aperture limit in $\sigma$ units, $\tau_x$ is radiation dumping time ( approximately $10ms$ for CESR), we can find that $A = 5.5\sigma_x$ corresponds to $20min$ beam life time and $A = 6.0\sigma_x$ gives $300min$. The life time $30min$ used as criterion for minimum pretzel in experiment is in this range.

Based on this observation we can make an important statement. If tracking shows that particles started with $6.0\sigma_x$ of horizontal amplitude are not getting lost, we can expect a good beam life time in experiment, if they are being lost, the beam life time is going to be short. This will be used as the criterion for a good beam life time in simulation below.

# 4 Beam current limit for CESR Phase II

At CESR Phase II operation, each counter-rotating beam consists of 18 bunches grouped into nine trains. There are 280 ns between train 1 and 2, 280 ns between train 2 and 3, and 294 ns between train 3 and 4. Then the pattern repeats. Bunches in the trains are separated by $42ns$ or $28ns$. In tracking below we used $42ns$ bunch spacing. CESR's optics L9A19C401.FD93S_4S_15KG and one of the save sets, "csr_set.48537", for electron injection condition was converted into MAD-input file and 36 BEAM-BEAM elements located at parasitic interaction points were added to simulate LRBBI. The result of this simulation is shown on figure 4.

The contours represent the maximum horizontal amplitude without beam loss for different combinations of bunch current and pretzel amplitude (arbitrary units). Shaded area shows region where $6\sigma_x$ particles survived for all tracking time, i.e., a good beam life time region. Figures 4 $a$ and 4 $b$ show tracking result for leading and for following bunches in train. For leading bunch tracking, figure 4 $a$. the good life time region does exist for current up to $11mA$, and has upper and lower pretzel limits. Upper limit is determined by available mechanical aperture, i.e., beam orbit distortion driven by pretzel becomes too large, so $6\sigma_x$ particles are getting out of mechanical aperture. This limit depends on current because of linear lattice distortion caused by LRBBI. At the lower limit the $6\sigma_x$ particles are getting to close to opposite beam. It results in the development of vertical instability by LRBBI. With the current increase the good life time region becomes smaller and for current bigger than $11mA$ it is vanished. For the following bunch, see picture 4 *b*, good life time region is propagated up to $14mA$. The reason for difference between these two bunches is the following. The pretzel using for beam orbit separation during colliding is antisymmetric relative to the main IP. It produces crossing angle and zero beam orbit displacement at main IP. To separate beams here during injection, a symmetric local pretzel bump generated by the two nearest horizontal separators is applying. This combination of symmetric and antisymmetric pretzels around the IP leads to the different beam orbit separation in parasitic points located on East and West sides from main IP. Since the positron trains are coming from East to West, the leading bunches in trains will see interaction at main IP and then parasitic interaction on *West* side while the following bunches will see parasitic interaction on *East* side. Because of the difference in separation, there is a difference in LRBBI. The above explanation is illustrated with figure 5. Note that in tracking we varied only the antisymmetric part of the pretzel keeping the part responsible for beam orbit separation at the IP at a constant level that was in injection save set "csr_set.48537".

Summing results for the both, leading and following bunches, we may conclude that for a given CESR Phase II optic and beam configuration (9 trains, 2bunches per train, 42ns bunch spacing), the beam current limit is about $11mA$ per bunch or $201mA$ of total current per beam at $1900 \div 2000$ units of pretzel. This limit is caused by LRBBI at the parasitic point nearest to main IP in injection condition. It should be mentioned that this limit was calculated for the vertical emmitance of the opposite beam equal to $\sigma_z^2/\beta_z = 2.7 \cdot 10^{-9}m$ that is usual for colliding. However it was found that the increase of the vertical size of the opposite beam leads to higher LRBBI limit, see [8]. In the present it is used to improve electron injection efficiency against stored intensive positron beam. Vertical size of positron beam is artificially blown up during electron injection. The limit calculated above for given vertical emmitance of positron beam is not applying for this condition.

# 5 Beam current limit for CESR Phase III

According to plans, see [9], CESR Phase III will have 9 trains containing 5 bunches each, with $14ns$ spacing between bunches. The total number of bunches will be 2.5 times higher than in present and the beam current should be about $500mA$ per beam. This intention to have so intensive counter-rotating beams sharing the same beam pipe should be confirmed by simulation of LRBBI limit. To study this limit we used "it_33_l62" optic for CESR Phase III provided us by David Rubin. This optic was designed using minimal criteria for beam separation as described in [9]. Applying software $Z2MAD$ we converted above optic into MAD-input file with no sextupoles and without steering magnets nonlinearities. To simulate LRBBI at parasitic interaction points 90 BEAM-BEAM elements were placed at their locations. "it_33_l62" optic contained the following deflection angles for the horizontal separators: K08W,E = $\pm 0.561mrad$ and K45W,E $\mp 0.713mrad$ [‡]. This set of deflections provided asymmetric pretzel with $\pm 2.65$ mrad crossing angle and zero displacement at the main IP. To separate beams there during injection symmetric local bump generated by equal deflection angles at K08W and at K08E is applying. It is on figure 5. There are also indicated the locations of the first five parasitic crossing points next to IP seen by bunch leading in the train traveling from the left side of picture to the right. Since the injection pretzel produces smaller beam orbit separation at those points we can expect that beam intensity will be limited by LRBBI during injection. It was confirmed by tracking described below.

To simulate beam intensity limit caused by LRBBI in colliding conditions we generated a MAD-input file using colliding pretzel and then dismissed the BEAM-BEAM element in main IP. The result of tracking under this condition is shown on figure 6 a. Here we used a crossing angle as parameter to describe pretzel amplitude. According to this result LRBBI should not limit the beam

[‡] $0.855mrad$ deflecting angle corresponds to $\pm 100kV$ voltage at $5.29GeV$ of beam energy

intensity up to level of $14mA$ per bunch or $630mA$ of total current per beam if crossing angle equals to $3.2mrad$. However situation is quite different for injection, see figure 6b. Here, due to smaller beam orbit separation at parasitic points (compare "Colliding" and "Injection" pretzels on figure 5) LRBBI becomes much stronger. It results in that there is not good beam life time region for current higher than $6.5mA$ per bunch, which is not acceptable for Phase III project.

Fortunately, at injection we can increase vertical beam emmitance in order to increase LRBBI limit, see [8]. Figure 6 c shows result of tracking with the vertical size of the opposite beam four time bigger than in tracking shown on figure 6 b. One can see that in this case, the good beam life time region, i.e., region without $6\sigma_x$ particles lost, is continued up to $12 \div 15mA$. It confirms capability of Phase III upgrade project. However, it should be mentioned that the above result was obtained with ideal field in final focusing magnets and without sextupoles and nonlinearities generated by vertical steering magnets. More reliable simulation with these imperfections added in model will be done in near future.

# 6 Conclusion

Using software $Z2MAD$ developed in [10] we generated MAD-input file that included BEAM-BEAM elements to simulate LRBBI in parasitic interaction points, collimators to represent mechanical aperture limitation and all known nonlinearities of magnetic field around ring.

Comparing experiment and corresponding tracking we established that the beam life time degradation observed in experiment correlates with that observed in tracking the loss of particles oscillating between $6\sigma_x$ and $5.5\sigma_x$ of horizontal amplitude. We concluded if $6\sigma_x$ particles are not lost in tracking, a good beam life time is expected in experiment. This has been used as a criterion for good beam life time in CESR Phase II and in CESR Phase III tracking data analysis .

Tracking made for *CESR Phase II* optic with 9 trains, 2 bunches per train and $42ns$ bunch spacing shows that beam current limit is caused by LRBBI at the level of $11mA$ per bunch or $201mA$ per beam. This limitation occurred during injection due to LRBBI at the nearest to main IP parasitic interaction point. Note that LRBBI limit depends on the vertical beam emittance. The $11mA$ per bunch limit is for $\sigma_z^2/\beta_z = 2.7 \cdot 10^{-9}m$. For bigger vertical emmitance LRBBI limit is higher.

The preliminary tracking for *CESR Phase III* optic with 9 trains, 5 bunches per train, $14ns$ bunch spacing shows that the LRBBI limit is at level of $6mA$ per bunch due to inadequate separation at the parasitic interaction nearest to main IP point. Fortunately, the increase of vertical beam emittance from $\sigma_z^2/\beta_z = 2.7 \cdot 10^{-9}m$ to $\sigma_z^2/\beta_z = 4.3 \cdot 10^{-8}m$ leads to higher LRBBI limit, which is enough to provide Phase III design parameters. The tracking for CESR Phase III did not include some magnetic field nonlinearities which may effect the final result. Since that this tracking should be repeated using more realistic condition.

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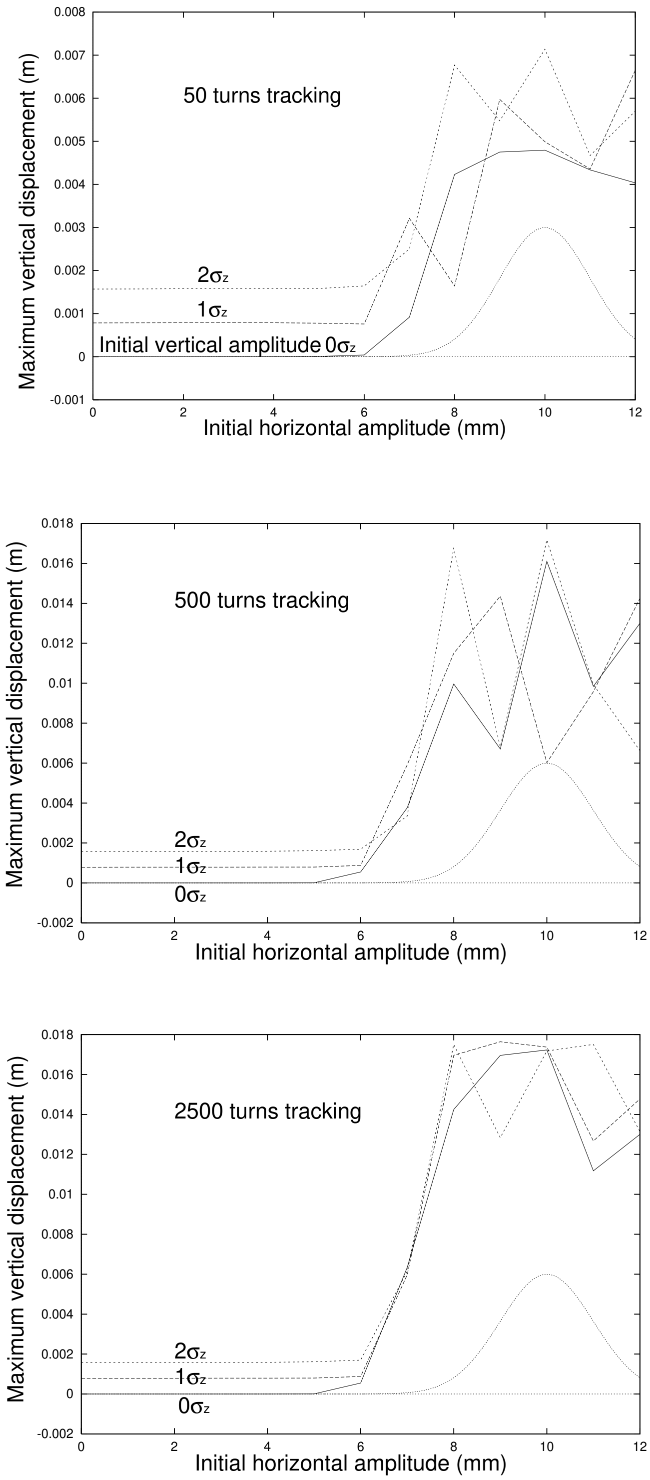
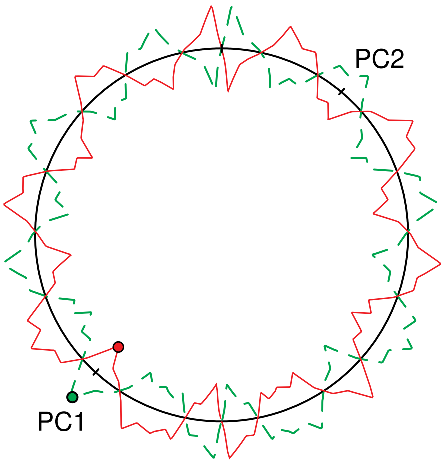



Figure 1: Maximum vertical displacement for 2500, 500 and 50 turns. Curves on each plot present tracking results for particles with 0, $0.26mm(1\sigma_z)$ and $0.52mm(2\sigma_z)$ initial vertical amplitude. Dashed line shows the location and horizontal profile of the opposite beam. Tracking was done for the following parameters at the PC. Horizontal and vertical beam orbit separation: $x_s = 10.0\,mm$, $y_s = 0.01\,mm$. Horizontal and vertical beam size: $\sigma_x = 1.0\,mm$, $\sigma_y = 0.26mm$. Vertical beta function - $\beta_y = 27.5m$. Betatron phase advance between interactions: $\mu_x = 2\pi \cdot 10.52$, $\mu_y = 2\pi \cdot 10.56$. Number of particles in opposite beam: $N_p = 3.2 \cdot 10^{11}$ ( 20mA of CESR's current).




Optics N9A19C501.FD93S_4S

| Parameters | PC1 | PC2 |
|---|---|---|
| $\beta v$[m] | 8.59 | 10.3 |
| $\beta h$[m] | 33.84 | 19.5 |
| Dispersion [m] | 0.21 | 1.36 |
| $\sigma h$[mm] | 1.20 | 1.55 |
| $\sigma v$[mm] | 0.30 | 0.23 |
| **Separation for 1000 units of pretzel** | | |
| Horizontal[mm] | 8.2 | 8.92 |
| Vertical[mm] | 0.004 | 0.001 |

Figure 2: Two parasitic points experiment configuration.

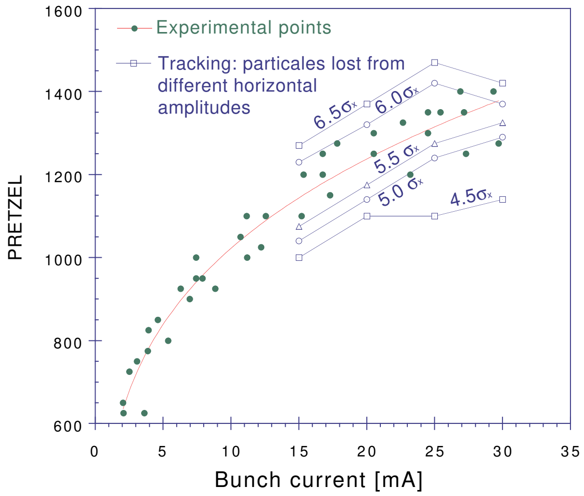



Figure 3: Minimum pretzel versus current for two parasitic points experiment. Solid are experimental points showing minimum pretzel required for $30min$ life time of the probe bunch as a function of strong bunch intensity. Open points show result of tracking. Parameters of PCs are given on figure 2.

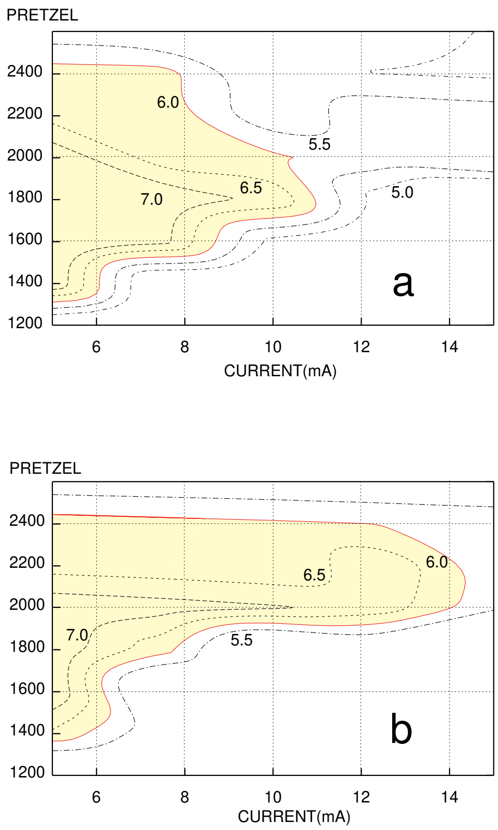



Figure 4: Tracking for CESR Phase II. Beam configuration: 9 trains, 2 bunches per train, $42ns$ bunch spacing. Figure “a” is tracking for leading positron bunch, “b” is for following. Shown are the pretzel levels corresponding to particles lost from different horizontal amplitudes as a function of beam current. Shaded area shows region with no $6\sigma_x$ particles lost, i.e., good beam life time region.

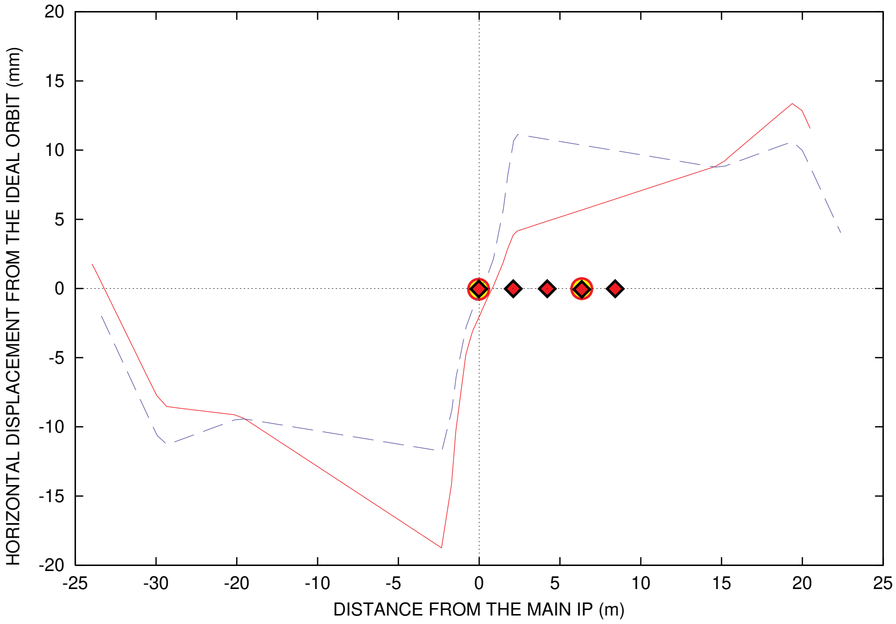



Figure 5: Injection (solid line) and colliding (dashed line) pretzel configuration around the main IP. Circles show the main IP and the first PC for leading bunches for two bunches train configuration with $42nsec$ bunch spacing (CESR Phase II). Diamonds are for the main IP and PCs seen by leading bunch for five bunches train configuration with $14nsec$ bunch spacing (CESR Phase III). Given parasitic crossings are for trains coming from left side of picture to the right.

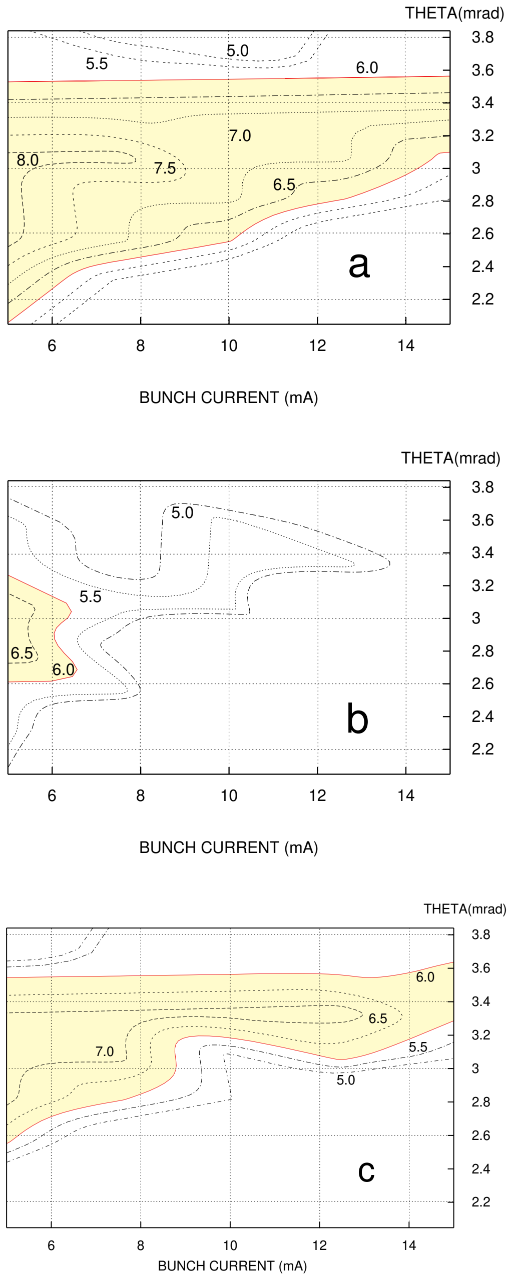



Figure 6: Tracking for CESR Phase III. Beam configuration: 9 trains, 5 bunches per train, 14ns bunch spacing. Tracking made for positron bunch leading in train. Shown are the pretzel levels corresponding to particles lost from different horizontal amplitudes as a function of beam current. Shaded area shows region with no $6\sigma_x$ particles lost, i.e., expected good beam life time region. Figure "a" is the effect of LRBBI for colliding stage. Interaction in the main IP was excluded. Figure "b" is tracking made for injection. Figure "c" is result of tracking for injection condition with vertical beam size of the opposite beam four times bigger than that used for figure "b".