CERN - European Laboratory for Particle Physics

CLIC Note 289
21 July 1995

Kink Instability for Small Crossing Angles

O. Napoly and B. Zotter

Abstract

The "kink instability" was found to require too small jitter tolerances for small angle crossings in CLIC with more than 2 bunches/beam. In order to permit 4 or even 10 bunches, larger crossing angles have to be used which require "crabbing" to counteract a severe loss of luminosity due to insufficient overlap at the IP.

Geneva (Switzerland)

1 Introduction

In order to increase the luminosity of CLIC without introducing too much disruption and energy spread, it is desirable to use bunch trains of 4 to 10 bunches per beam[1]. However, in CLIC the bunches need to be quite closely spaced (20 cm) and they have to be separated transversely in order to avoid severe blow-up at the parasitic crossings. For a flat beam spot, a horizontal crossing angle is the best solution. However, if the crossing angle exceeds the "diagonal angle" ($\approx \sigma_x/\sigma_s$), the overlap of the bunches at the IP (interaction point) is reduced and a severe loss of luminosity results.

In order to counteract this loss it has been proposed to use "crabbing", i.e. rotating the bunches such that they overlap completely at the IP. This can be achieved e.g. by kicking the ends of the bunches in opposite direction in an RF cavity upstream, such that they turn by just half the crossing angle at the IP. The required transverse fields are high but not unreasonable, but the necessary phase stability to avoid incorrect rotation of the bunches was found to be extremely tight, about 1/20 degree for the CLIC parameters then valid[2]. This value [2] can be somewhat relaxed for the larger aspect ratio of the beam spot in the new parameter list, but is still only a small fraction (1/6) of a degree. Another problem may be an incomplete compensation of the vertical dispersion introduced by horizontally inclined trajectories in the strong solenoidal field required over the interaction region for experiments. In addition, this method has never been tried experimentally.

A crossing angle smaller than the diagonal angle would eliminate the need for crabbing, and reduce considerably the vertical dispersion introduced by a solenoidal field. It also permits passing the outgoing beam through the beam hole of the high beta quads next to the IP. Since the outgoing beams are strongly "disrupted" (i.e. widened), the beam holes have to be somewhat enlarged, in particular when the quads are aligned with the axes of the incoming beams to avoid emittance growth due to enhanced synchrotron radiation in large off-axis fields. Such a design for CLIC has been studied[3], and a solution was found using high beta quadrupoles with apertures of 12 mm in the first, and 20 mm in the second one, assuming a maximum pole tip field of 1.4 T. Such quads could thus be of the "hybrid" type (precision iron pole pieces magnetized by permanent magnets) originally proposed[4] to get high gradients with good stability. With such quads, additional beam clearance is provided by the fact that there is no material in both the horizontal and the vertical planes of such a quad up to much larger dimensions. However, it should also be possible to use superconducting quadrupoles with higher fields and larger apertures.

Horizontal kicks due to parasitic crossings will shift the interaction point slightly, and lead to a small increase of the horizontal spot size - of the order of a few percent - due to the energy spread of the beam[5]. However, the effect of vertical kicks of both the parasitic and the main crossing appears to be much stronger, although it disappears for perfectly aligned beams. A vertical jitter of one tenth of a sigma - i.e. less than a micron at the exit of the linac where $\sigma_y = 3\mu$m for $\beta_y = 10$ m - has been found to reduce luminosity by over 20 % already for 2 bunches/train, and close to the single bunch luminosity for 4 or more bunches.

2 Analytic estimates

The name "kink instability" comes from plasma physics, where pinching of a plasma column for thermo-nuclear fusion was found to be limited by sudden sideways motion of part of the beam. In linear colliders, a similar sideways motion was found to explain the difference between simulations of the beam-beam interaction: in one study[6]luminosity enhancements well above a factor 20 at very high disruption were found, while in several others a factor 6 was never exceeded[7]. This discrepancy was traced back[8] to the perfect symmetry assumed in the first model which artificially eliminated any sideways motion by symmetry requirements.

The phenomenon reappeared in subsequent studies of the effect of vertical offsets of bunch trains with horizontal crossing angles. The focussing effect of such a crossing is enhanced at the next one and leads to a stronger deflection at the interaction point, and hence loss of luminosity the higher the number of bunches. The problem was summarized in a simple criterion for the permissible number of bunches in a train (before they are separated in individual channels at the face of the first quad)

$$(n_b - 1) < \frac{2}{D_x D_y} \tag{1}$$

Unfortunately, the author had dropped a term $(\theta_c/\theta_d)^2$ on the RHS, i.e. the square of the ratio of crossing to diagonal angle which he assumed to be usually about one - but which it rarely is. For the present CLIC parameters, $D_x = 0.286$ and $D_y = 9.544$, the maximum number of bunches, ignoring the angle ratio, is 1.73, i.e. 2 bunches would be marginally possible. However, for a crossing angle of 0.52 mrad, and a diagonal angle of 1.25 mrad, the maximum is actually reduced to 1.13 and only single bunch operation would be reasonable. Crossing angles well in excess of the diagonal angle - e.g. 5 mrad - would be needed for obtaining the desired increase of luminosity with 10 bunches - assuming they fully overlap.

3 Computer Models

In order to verify these predictions, two computer programs were written: the first one assumed a purely linear model for the beam-beam kick, and calculates the trajectories of the bunches by matrix multiplications. The luminosity reduction can be obtained from the assumed jitter amplitudes and distributions. However, the assumption of a linear beam-beam force is only correct for small displacements, and becomes an overestimate for larger ones.

Therefore a second program was written to include also the nonlinear part of the beam-beam interaction. The luminosity reduction is obtained by averaging over a large number of initial conditions for the trajectories. A number of different models for the beam-beam force were tested, but in general the results of the simulation agreed almost perfectly with those of the linearized model.

Some results are shown in the attached figures. For the small crossing angle of 0.52 degrees, Fig.1 shows the luminosity reduction as function of the vertical jitter amplitude (divided by σ_y), assuming a constant angular jitter of 0.1 $\sigma_{y'}$, for 2 bunches/beam. Already for a jitter amplitude of 0.1 σ_y, i.e. 0.3 μm at the end of the linac, the reduction is more than 20 %. For 4 bunches (Fig.2), the reduction reaches more than 40 % already with a 10 times smaller jitter, while for 10 bunches (Fig.3), only the single bunch luminosity is left over even for minimal jitter. For a 2 mrad crossing angles, the situation is slightly better (Fig.4), and 4 bunches could be used if the jitter is small. With a 5 mrad crossing angle (Fig.5), even 10 bunches would be acceptable from this point of view.

These figures were obtained with the simulation program SKINK, but the linearized program MKINK gave undistinguishable results in all these cases.

4 Conclusions

We investigated the effect of the "kink instability", due to both the main and parasitic beam-beam kicks, when vertical jitter is included in an interaction region with a horizontal crossing angle. The strong deflections even for very small jitter will not permit operation of CLIC with a small crossing angle with present parameters for 500 GeV c.o.m., without severe loss of luminosity for more than 2 bunches. A crossing angle in excess of the diagonal angle would avoid this problem, but requires"crabbing" of the bunches to keep the luminosity high. Crabbing has never been tried experimentally yet, and a number of problems - such as extremely high phase stability - need to be solved in order to use it to its full potential.

References

[1] G.Guignard, I.Wilson, CLIC-Note 264 (1994)

[2] J.Hagel, B.Zotter, CLIC Note 210 (1993)

[3] S.Kheifets, B.Zotter,CLIC-Note (1995)

[4] T.Taylor et al, SF Conference paper 1989

[5] O.Napoly, B.Zotter, CLIC-Note 254 (1994)

[6] P.Chen, SLAC-Pub 4822 (1988)

[7] R.Hollebeek, NIM 184, p.333 (1981)

[8] Capri workshop on Linear Colliders, 1986

[9] M.Bassetti, D.Erskine, CERN-ISR-TH/80-06 (1980)

Appendix: The Simulation Program SKINK

This program has been written to extend the matrix multiplication routine MKINK which - in addition to the deflections by parasitic crossings - assumes a purely linear beam-beam kick. This approximation is correct only for small transverse displacements, but becomes a substantial overestimate of the kick when the displacement exceeds a few times the rms size of the bunch. In the simulation one can choose the proper nonlinear expression for flat beams[9] or a linear kick for comparison with MKINK, in addition to the case without beam-beam kicks. The program plots the luminosity reduction as function of amplitude jitter, for a fixed angular jitter, and averages over a large number of initial conditions. The input parameters are read from the files CLIC.BEAM and the most important ones are printed on the graph.

Both programs reside on the HPARIEL computer in the SL/AP division, under user zotter/napoly, the first one in the directory MKINK and the second one in its subdirectory SIMUL. There are executable versions for both MKINK and SKINK which read the respective data files and produce a graphical output.

Since it was not obvious to find the proper expression for the beam-beam kick of an elliptic bunch, as usually only the expressions for the fields are given, we repeat here the expression used in the program

$$\begin{aligned}\Delta x' - i\Delta y' \;=\; & \frac{2Nr_e}{\gamma}\frac{i\sqrt{\pi}}{\sqrt{4(\sigma_x^2-\sigma_y^2)}}\left[\mathrm{w}\left(\frac{x+iy}{\sqrt{4(\sigma_x^2-\sigma_y^2)}}\right)\right. \\ & \left. -\ \exp\left(-\frac{x^2}{4\sigma_x^2}-\frac{y^2}{4\sigma_y^2}\right)\mathrm{w}\left(\frac{x/R+iyR}{\sqrt{4(\sigma_x^2-\sigma_y^2)}}\right)\right] \qquad (2)\end{aligned}$$

with $R = \sigma_x/\sigma_y$, and where w(z) is the complex error function.

Acknowledgements:

We would like to thank S. Farthouk for useful discussions, as well as A. Sery and E. Keil for help with expressions for the beam-beam kick.

FIG 1 LUMINOSITY REDUCTION FACTOR vs. BEAM JITTER AMPLITUDE

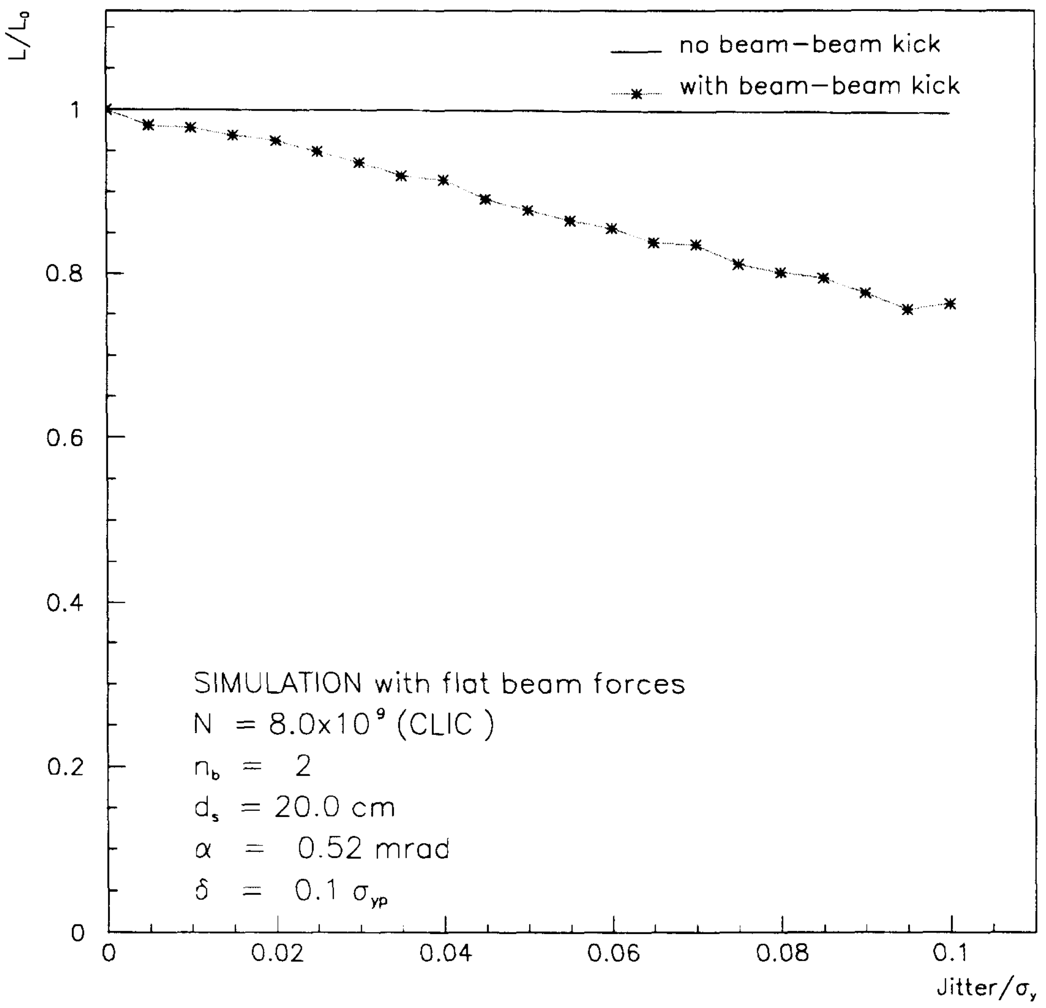

Figure 1: 2 Bunches/beam with 0.52 mrad crossing angle

FIG.2 LUMINOSITY REDUCTION FACTOR vs. BEAM JITTER AMPLITUDE

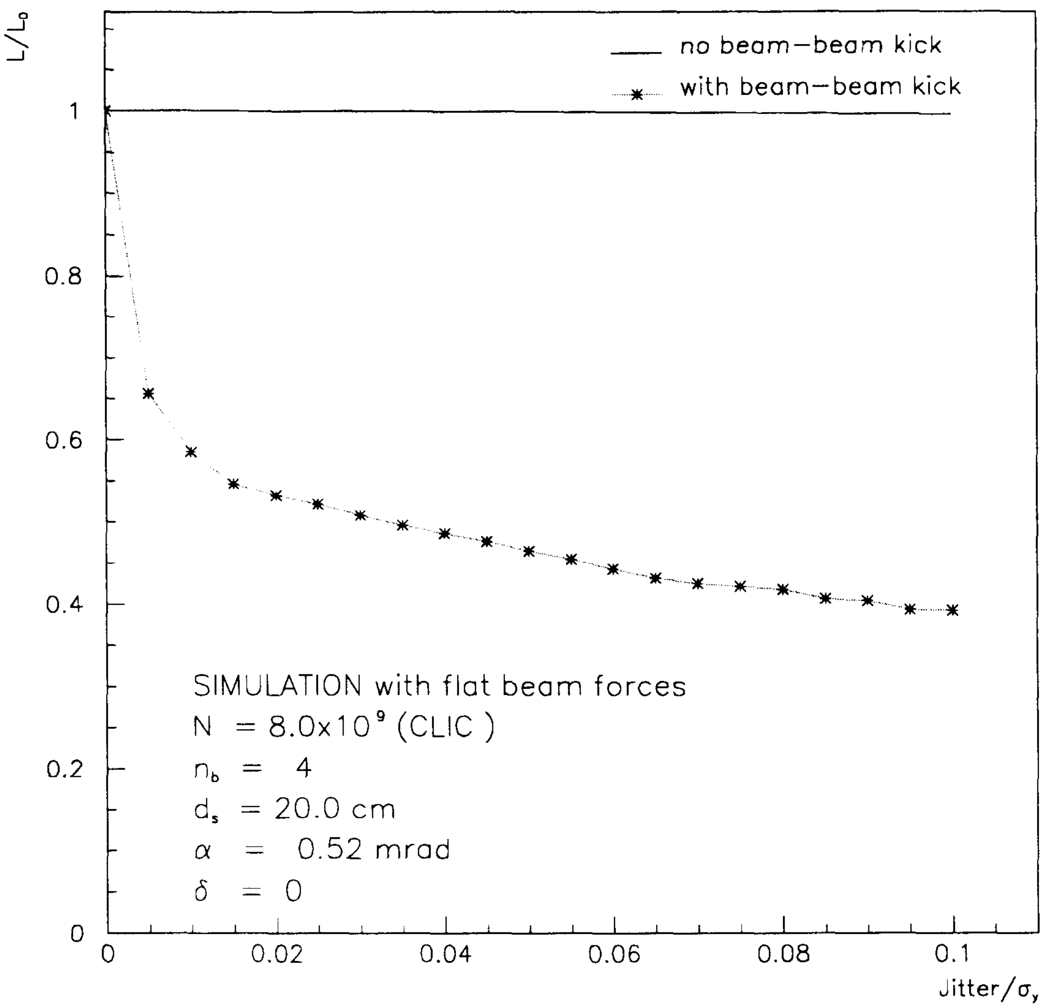

Figure 2: 4 Bunches/beam with 0.52 mrad crossing angle

FIG.3 LUMINOSITY REDUCTION FACTOR vs. BEAM JITTER AMPLITUDE

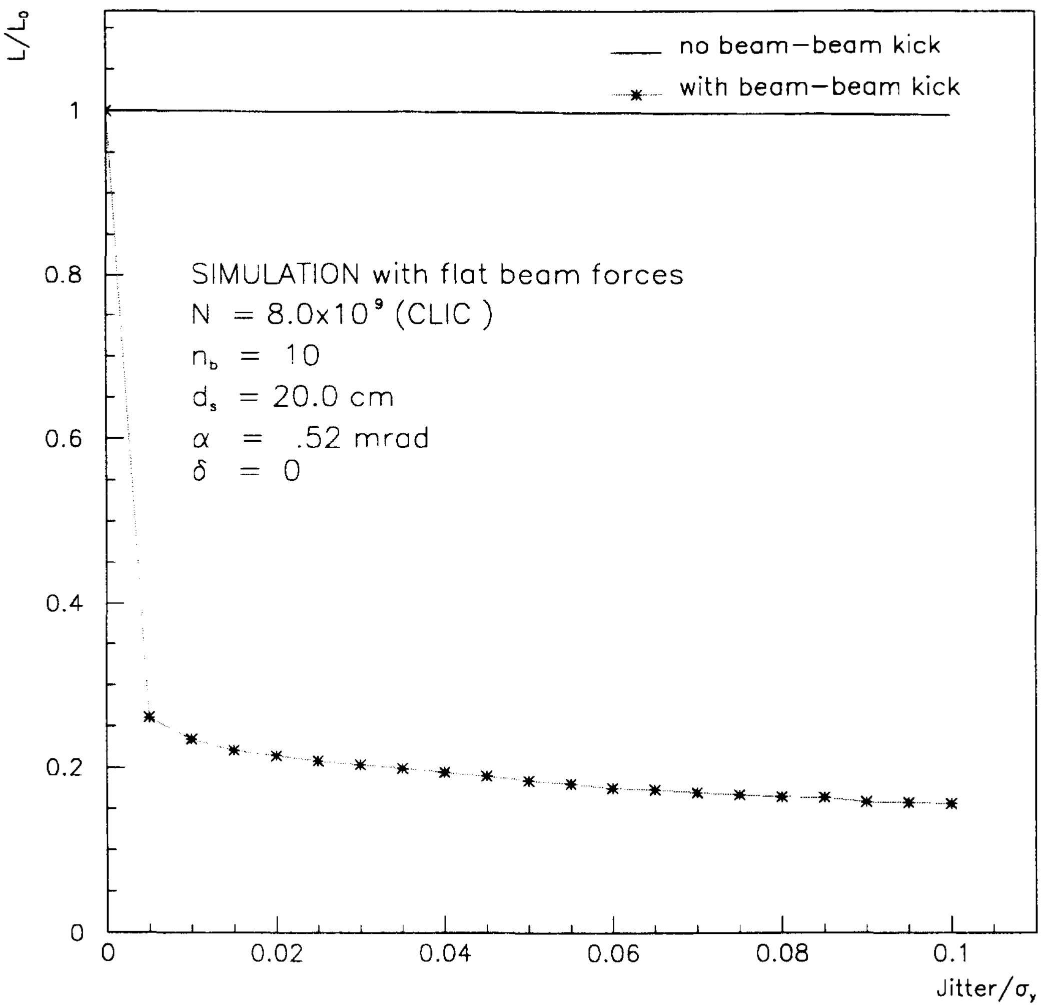

Figure 3: 10 Bunches/beam with 0.52 mrad crossing angle

FIG.4 LUMINOSITY REDUCTION FACTOR vs. BEAM JITTER AMPLITUDE

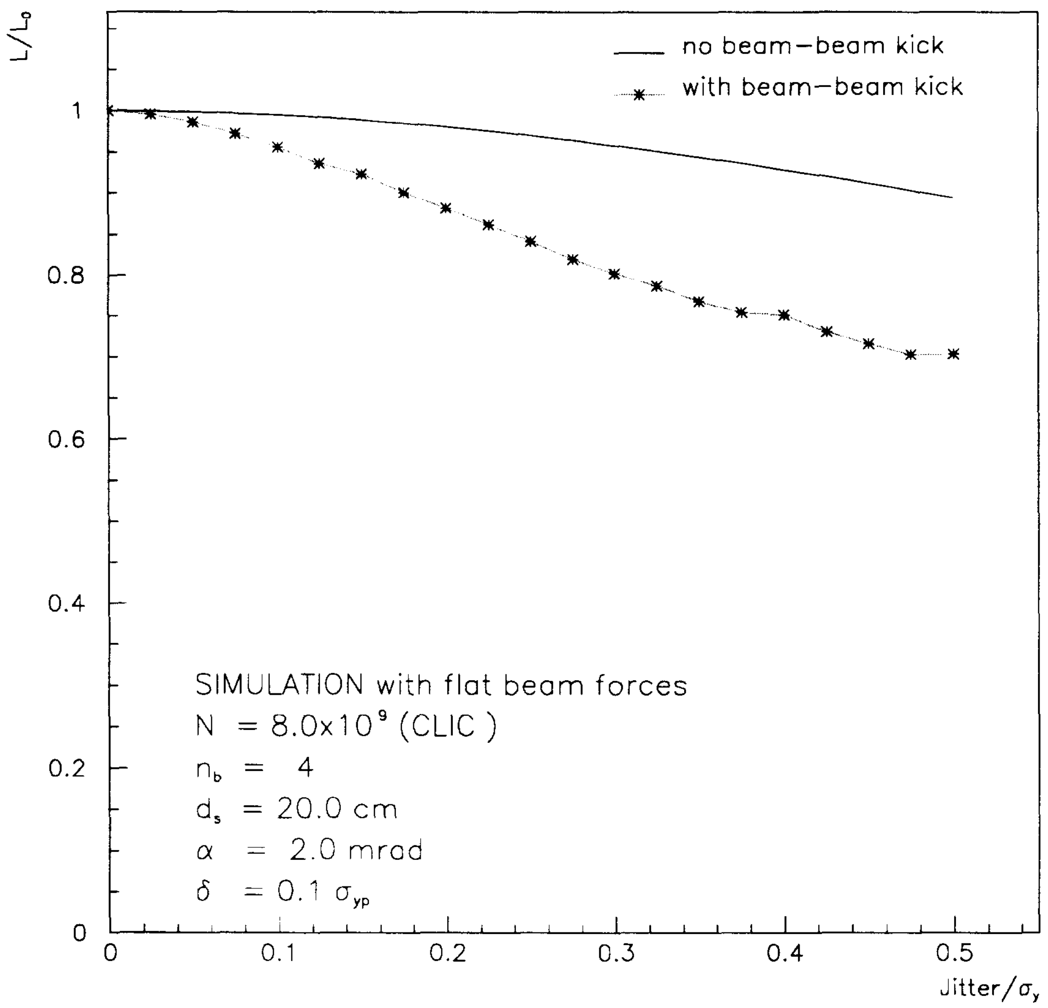

Figure 4: 4 Bunches/beam with 2 mrad crossing angle

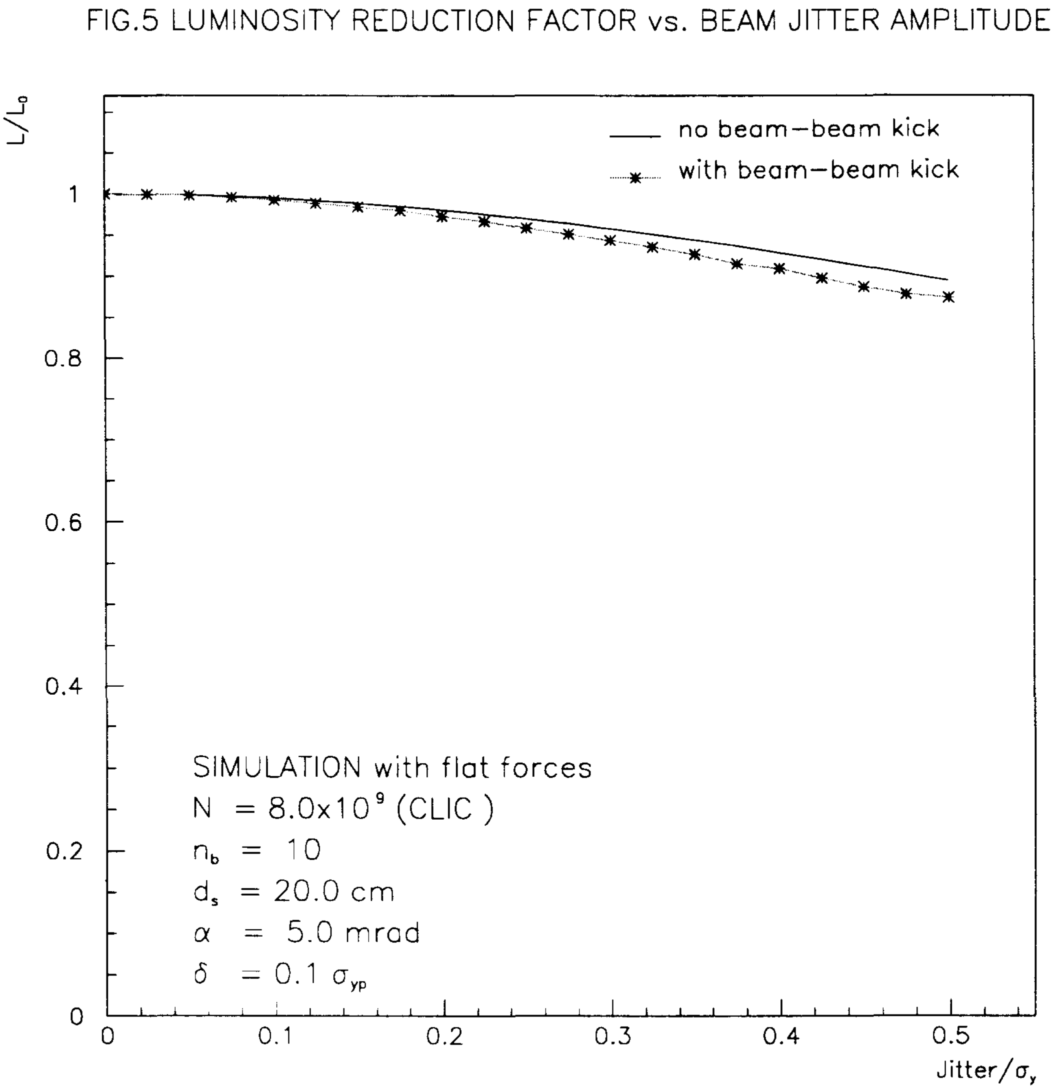

Figure 5: 10 Bunches/beam with 5 mrad crossing angle