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Evaluation of the Multi-Bunch Kink Instability in ILC Head-on Collisions

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Abstract

An interaction region with head-on collisions is considered an alternative to the baseline configuration of the International Linear Collider which includes two interaction regions with finite crossing-angles (2 and 20 mrad). Although more challenging from the point of view of the beam extraction, the head-on scheme is favoured by the experiments because it allows an easier optimisation of the detector configuration, particularly in the forward region. The optics of the head-on extraction is revisited, as compared to the TESLA TDR, by separating the e+ and e- beams horizontally, first by electrostatic separators operated at their LEP nominal field and then using a defocusing quadrupole of the final focus beam line. In this way the septum magnet is protected from the beamstrahlung power. The influence of parasitic collisions is shown to lead to a region of stable collision parameters.

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1 Introduction

An interaction region with head-on collisions is currently considered as an alternative to the baseline configuration of the International Linear Collider (ILC) which includes two interaction regions, one with a large crossing-angle (14 to 20 mrad) and one with a small but finite angle (2 mrad). Although more challenging from the point of view of the beam extraction at high luminosity and energy, the head-on collision scheme is favoured by the experiments because it offers a better detector legibility and hermeticity, particularly in the very forward direction.

The optics of the head-on extraction has been recently revisited [1] with respect to the TESLA TDR design. The e+ and e- beams are separated horizontally first by electrostatic separators operated at their LEP nominal field and supplemented by a defocusing quadrupole of the final focus beam line. In this way the septum magnet is protected from the incident beamstrahlung power.

As a consequence of the weaker electrostatic field, the beams are separated by about 10 mm at their first parasitic crossing, on both sides of the main interaction point (IP). In this note we investigate the influence of these parasitic crossings on the stability of the bunch train collisions and luminosity.

2 The beam parameters at collision

The beam parameters used for the study are the TESLA TDR parameters shown on the Table 1. By comparison, the ILC nominal parameters assume a weaker beam-beam interaction at the IP and hence should also improve the stability of the multi-bunch collisions. The bunch to bunch distance, assumed to be nominally Ds = 90 m (i.e. 3 MHz intra-bunch repetition rate) will be varied to investigate the limit of the stable regime.

			TESLA	ILC
Energy	[GeV]	:	250.	250.
Horizontal RMS at the IP	[nm]	:	553.	655
Vertical RMS at the IP	[nm]	:	5.	5.7
Horizontal normalized emittance	[µm.rad]	:	10.	9.6
Vertical normalized emittance	[nm.rad]	:	30.	40.
Longitudinal RMS	[mm]	:	0.4	0.3
Bunch population N		:	2.10^{10}	2.10^{10}
Number of bunches n_b		:	2820	2820
Bunch distance Ds	[m]	:	90.	90.
Repetition rate	[Hz]	:	5.	5.
Vertical Disruption Parameter	D_y	:	33.0	18.5

Table 1: TESLA and ILC beam parameters at collisions.

3 The Multi-Bunch Kink Instability (MBKI)

In the head-on collision scheme described in [1], the e+ and e- bunch horizontal separation at the distance $\pm Ds/2$ from the IP where the first parasitic crossing occurs is not large enough to separate the beams in two different beam chambers. The incoming and outgoing bunches are therefore experiencing parasitic beam-beam forces which, if too strong, can amplify the incoming beam jitter, hence degrade the IP luminosity and ultimately generate a multi-bunch kink instability. We concentrate here on the intra-train (bunch to bunch) vertical position jitter, characterized by its RMS value $\sigma_{\delta y}$ at the IP, since it is the most critical for the luminosity. By colliding with an offset δy^* at the IP, the outgoing bunches acquire a vertical kick from the beam-beam forces which increases their vertical separation with the next incoming bunch at the parasitic collision. Assuming that there is no interaction at the second parasitic collision at the distance ±*Ds*, the bunch with index *i* in the bunch train (i=1,n_b) therefore interact with the 3 bunches of index $i-1$, i (at the main IP), and i+1 of the opposite bunch train. The kink instability can therefore develop and influence the entire bunch train. Its magnitude depends on the bunch horizontal distance at the parasitic interaction points and on the RMS jitter value $\sigma_{\delta y}$ at the IP: the larger the horizontal separation, the weaker the Coulomb interaction at the parasitic crossings. The loss of luminosity resulting from this multi-bunch effect therefore potentially aggravates the loss of luminosity due to the IP jitter $\sigma_{\delta y}$ only, given by

$$L = L_0 . \frac{1}{\sqrt{1+\frac{\sigma_{\delta y}^2}{\sigma_y^2}}} \qquad (1)$$

where σ_y is the IP vertical spot size.

In this expression as well as in the rest of the paper, the incoherent beam-beam effect is not taken into account and no beam-beam simulation is made. Only the coherent beam-beam effect [2] which describes the global Coulomb interaction of the two flat bunches is accounted for. Like in a previous CLIC study [3], the loss of luminosity is calculated in the linear approximation where the dependence of the beam-beam kick is linearized with respect to the vertical beam separation both at the IP crossing and at the long distance parasitic crossing. This approximation, which is correct for small vertical offsets, overestimates the instability effect for large offsets. This is particularly true at the IP, as shown by Figure 1 which shows the IP coherent beam-beam kick angle as a function of the vertical separation for the TESLA TDR parameters. A calculation showing a regime of stable multi-bunch collisions should therefore be on the safe conservative side.

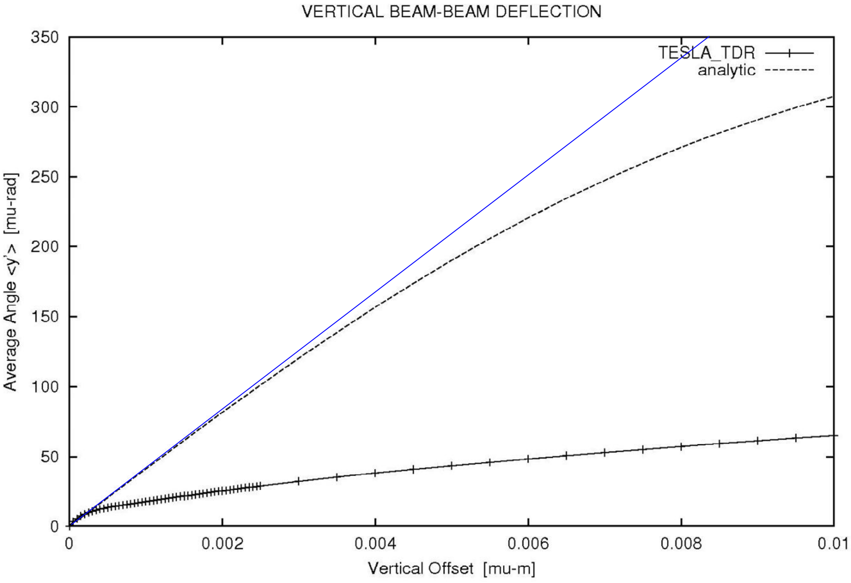

Figure 1: Evolution of the vertical beam-beam deflection considering three regimes: a) the line corresponding to the linear regime, b) the dotted curve corresponding to the theoretical regime with a rigid bunch and c) the TESLA TDR simulation.

We define *i* and *j* as the indexes of respectively the positron and electron bunches, *N* the number of particles in one bunch, s_{ij} the distance of the parasitic collision with respect to the IP, $s_{ij} = (j-i).Ds/2$.

- At the IP, i = j, the vertical angular kick is given in the linear regime by:

$$\delta y'_{ii} = -\frac{1}{f}\delta y_{ii} = -\delta y_{ii} D_y / \sigma_z \approx -\delta y_{ii} * 2Nr_e / (\gamma\sigma_y\sigma_x) \qquad (2)$$

  where D_y is the vertical disruption parameter, and $\delta y_{ii} = (y_i^+(s_{ii}) - y_i^-(s_{ii}))$ the beam-beam offset.

- At the parasitic crossing, i ≠ j, we consider only the action of the long range forces :

$$\delta y'_{ij} = -\frac{2Nr_e}{\gamma(\delta X_{ij})^2}.\delta y_{ij} = -\delta y_{ij} / F_{ij} \quad (2)$$

  where δX_{ij} is the distance of the bunches at the parasitic crossing.

4 The zero degree extraction system

The zero degree extraction system is shown on the figure 2.

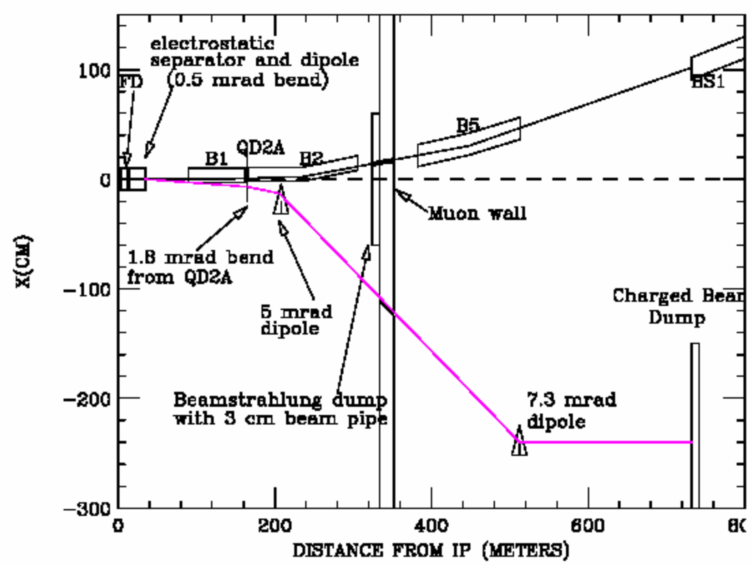

Figure 2: Zero Degree Extraction System from IP to charged beam dump.

We consider the existing 20 mrad FF optics that we can slightly modify as the head-on configuration allows us to eliminate the crab cavity system at 500 GeV CM. The distance between the IP and the beginning of the electrostatic separator can then be minimized to 10.5 m to increase the separation distance δX_{12} at the parasitic point at 45 m. Figure 3 shows the optics considered to evaluate the Multi-Bunch Kink Instability.

The length of the electrostatic separator is of 25 m. We simulate its optics with 25 cells, each giving a -0.02 mrad kick with two drifts of 0.5 m on each side. In our configuration, we achieve this way a 0.5 mrad global kick which corresponds to a δX_{12} of 10.97 mm at a distance $Ds/2$ = 45 m from the IP.

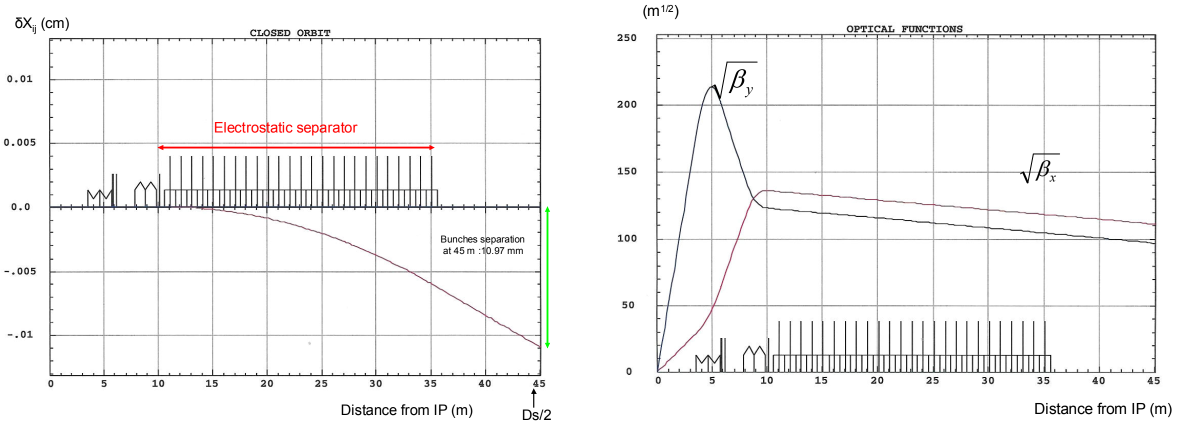

Figure 3: Electrostatic Separator scheme and the corresponding beta functions.

5 Simulations

Considering the optics of the final doublet, a generalization of the original multi_kink code [3] led to the results shown on the figures 4 to 7.

As the number of bunches increases, we see on the figures 4 to 7 that so does the MBKI. We then encounter three main regimes by varying the distance δX_{12} :

- on figures 4 and 5, a drastic loss in luminosity occurs, showing an unstable collision regime for a small separation δX_{12} = 7.9 mm.

- on figure 6, a limited loss of luminosity (30 %) considering 2820 bunches at a jitter of 0.5 σ_y is seen,

- on figure 7, using the nominal distance δX_{12}, the loss of luminosity coming from the MBKI is immediate but very limited and quasi-insensitive then.

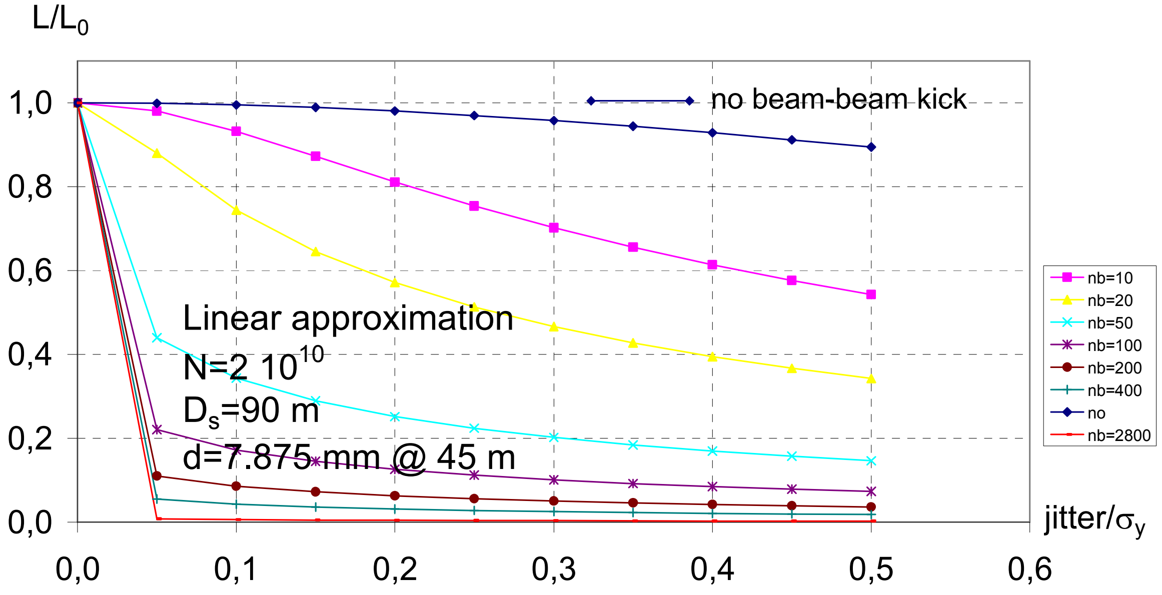

Figure 4: Behaviour of the luminosity versus the vertical jitter amplitude for different numbers of bunches considering δX_{12} = 7.875 mm.

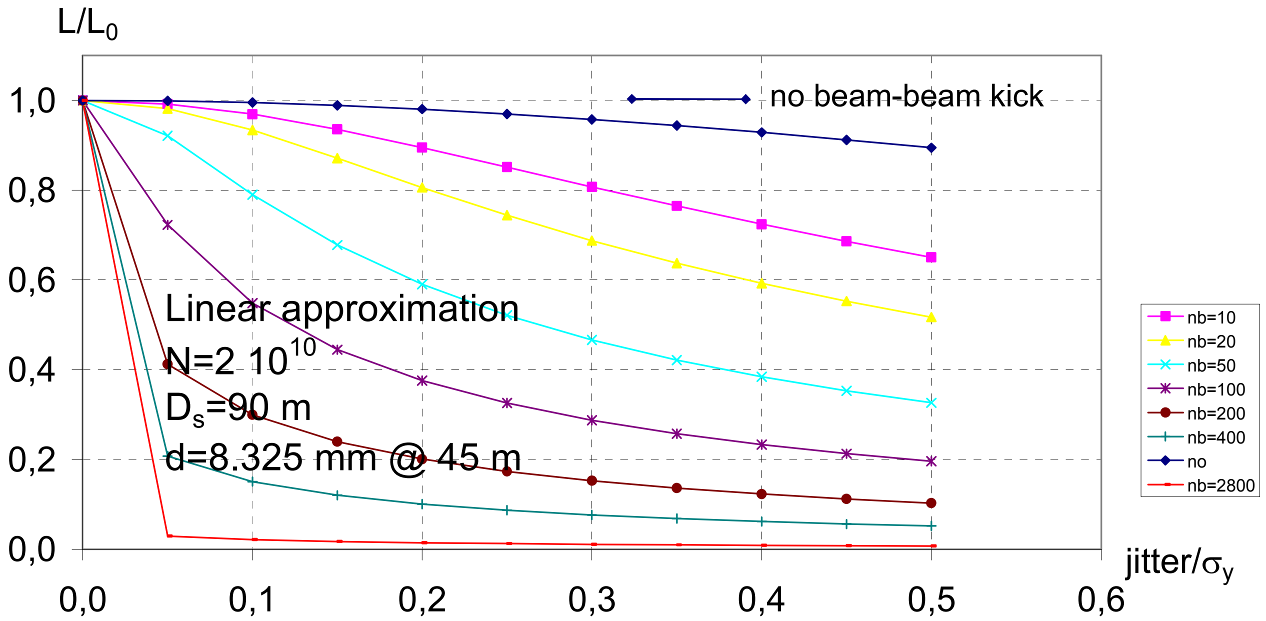

Figure 5: Behaviour of the luminosity versus the vertical jitter amplitude for different numbers of bunches considering $\delta X_{12} = 8.325$ mm.

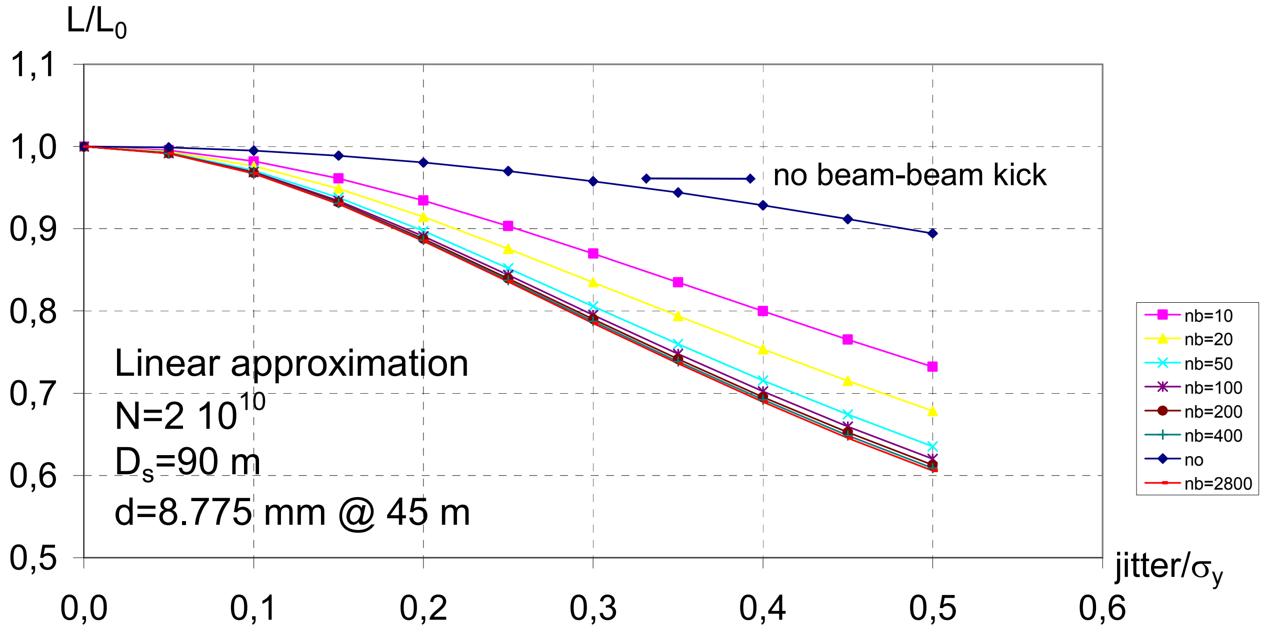

Figure 6: Behaviour of the luminosity versus the vertical jitter amplitude for different numbers of bunches considering a $\delta X_{12} = 8.775$ mm

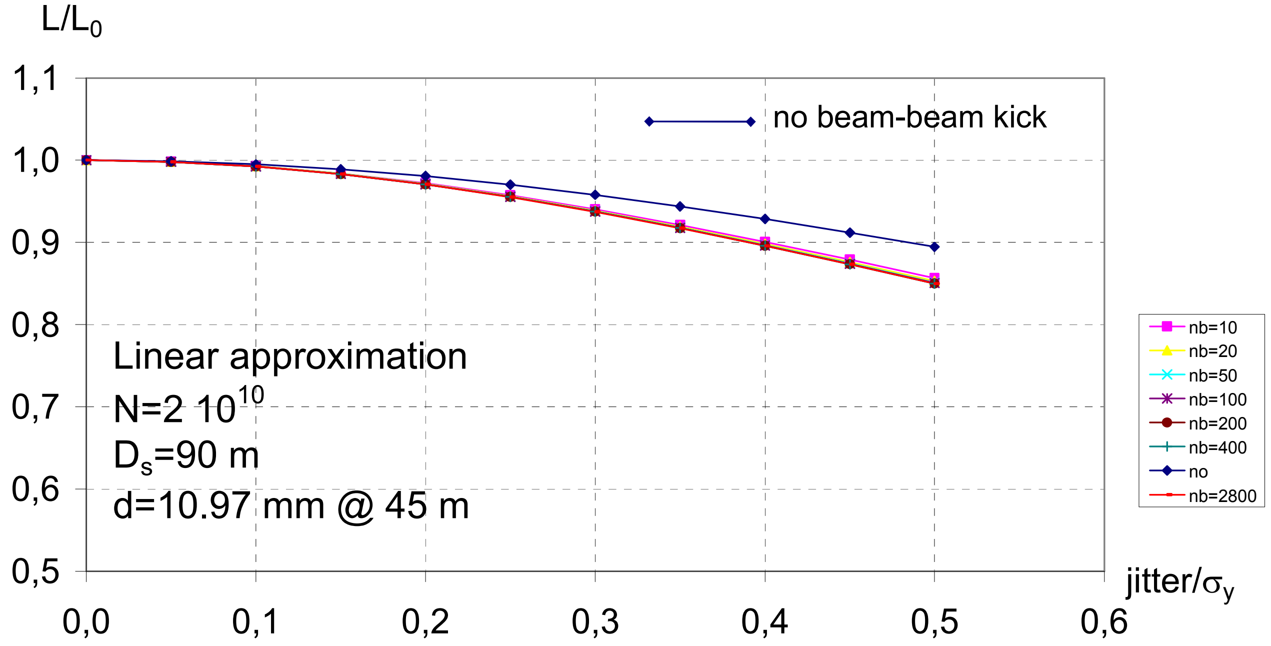

Figure 7: Behaviour of the luminosity versus the vertical jitter amplitude for different numbers of bunches considering the nominal $\delta X_{12} = 10.97$ mm.

By standing in a MBKI's limit regime shown on the figure 4 and varying at the same time δX_{12} and the bunch charge N, we maintain the luminosity curve identical, we can then plot $\delta X_{12}(mm) = f(N)$. The result found is shown on the figure 8. We illustrate the three regimes shown on the figures 4 to 7. The figure 8 presents a line of equation: $\delta X_{12}(mm) = 4{,}166.N(10^{10})$ that roughly delimits three areas at the nominal intensity of 2 10^{10}:

- two unstable close and close below the line at $\delta X_{12} = 8.325$ mm,
- one stable which is sensitive to the MBKI at $\delta X_{12} = 8.775$ mm,
- one stable which doesn't see the MBKI at the nominal value of $\delta X_{12} = 10.97$ mm

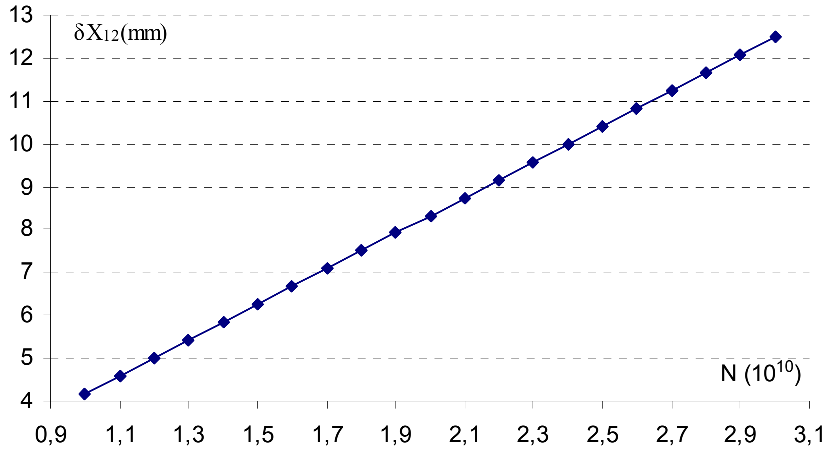

Figure 8: Behaviour of the separation parasitic collision distance δX_{12} versus the number of particles N of the beam.

At the limit of stability for the MBKI, the separation parasitic collision distance δX_{12} varies linearly with the charge of the beam N considering the modified MultiKink code of J. Payet. The validity of the results given in this note relies on this curve. The domain in intensity has been chosen around its nominal value of 2.10^{10} with a range spanning from 10^{10} to 3.10^{10}.

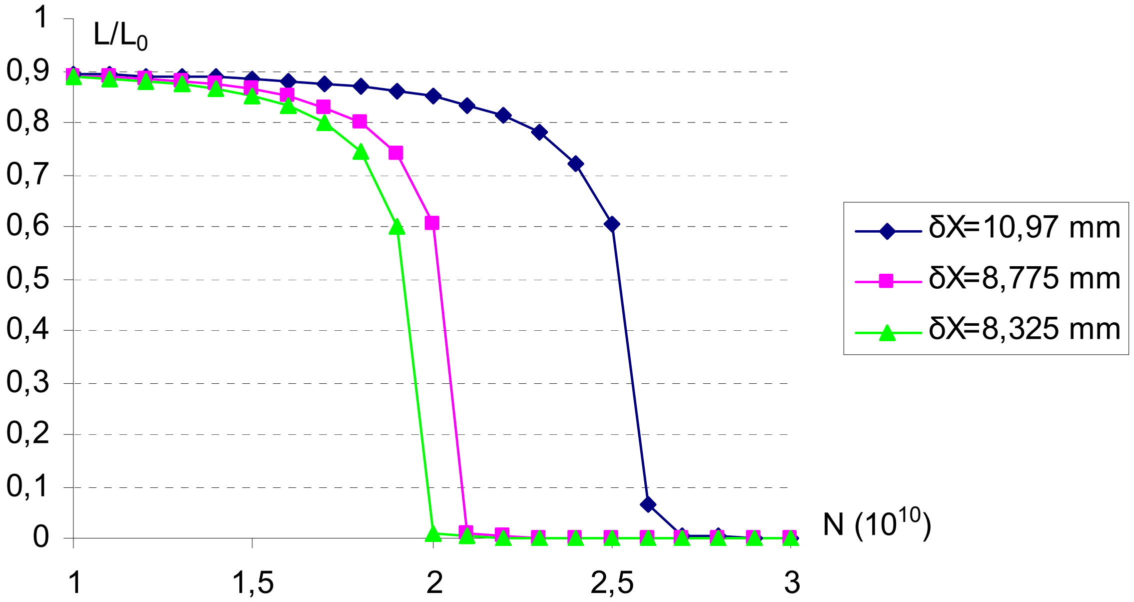

Figure 9. Evolution of the luminosity behaviour L/L_0 versus the bunch charge *N* for three different values of the parasitic crossing distance δX_{12} : a) at 10.97 mm, we are above stability and so we increase *N* up to 2.5 10^{10} without any problems, b) at 8.775 mm and below, we are below stability and we can barely go beyond the nominal value of N = 2 10^{10}.

Figure 9 shows the influence of the MBKI on the luminosity for the three previous values of δX_{12}. The loss in luminosity evolves smoothly from 0.9 till 0.6 with N then drops sharply for a specific value of *N* that corresponds to the seeked limit in stability.

Figures 10 and 11 illustrate the research of the optimum bunch separation *Ds* to minimize the MBKI impact on the luminosity *L*. First by considering a nominal charge *N* of 2.10^{10} particles at *Ds* = 90 m shown on the figure 10 (blue curve), we obtained finally an increase of 5.5 % of the charge by placing ourselves at *Ds* = 85 m. Considering the pink curve, we increase the bunch charge to *N* = 2.5 10^{10} to counteract the loss in current due to the increase of the bunch separation for *Ds* = 94 m.

The corresponding luminosity improvements are shown on the figure 11. We have an improvement of 5 % at 86 m and a maximum of 47 % at 92 m. It is interesting to mention that our starting *Ds* of 90 m seems to be an excellent compromise giving a possible improvement of 38 %.

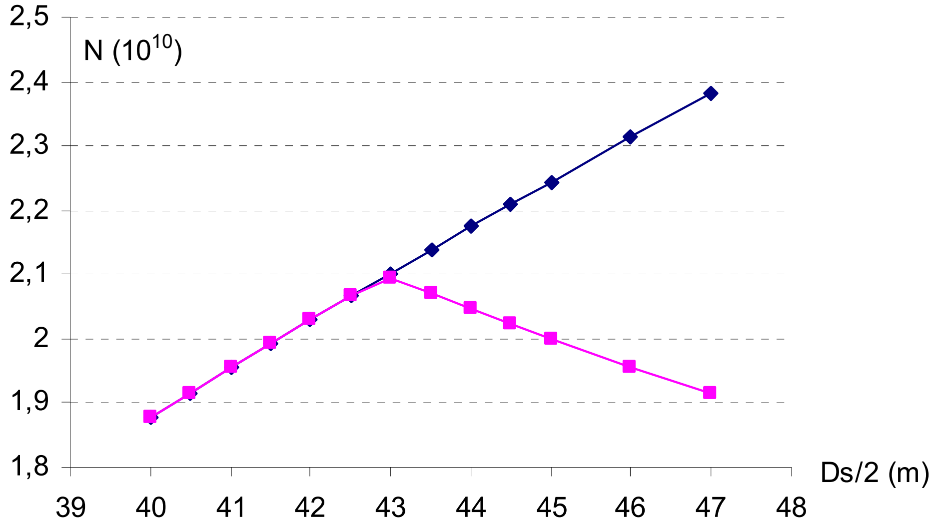

Figure 10: Evolution of the intensity of the bunch in function of the parasitic collision distance Ds/2 considering that the bunch charge is constant (blue line) or is increased keeping the MBKI small (pink line).

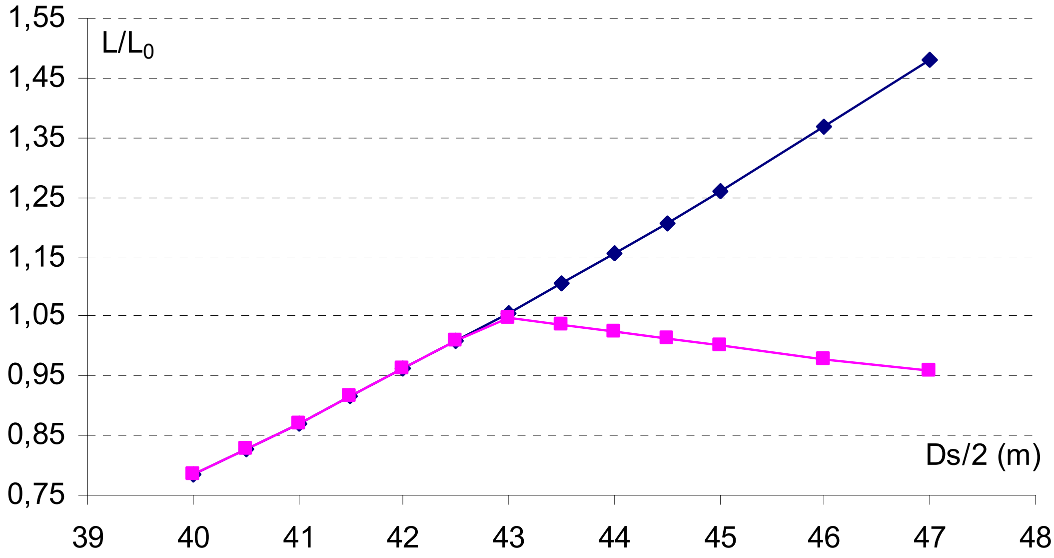

Figure 11: Evolution of the luminosity (normalized to L = 0.8 L_0 obtained for N = 2 10^{10} at Ds/2 = 45 m (pink line)) in function of the parasitic collision distance Ds/2: 1) keeping N constant, 2) increasing N while keeping the MBKI influence inferior to 10 % of loss in luminosity (blue line).

6 Conclusions and perspectives.

The Multi-Kink code considering only the vertical jitter in position δy_{ii} at the IP has shown that the MBKI was not a problem for our head-on scheme using the TESLA TDR parameters in our linear regime. Figure 1 shows that our kick might have been under-evaluated for small vertical offset. A deeper analysis might be needed. We can also achieve a good separation of the beams on a range spanning for *Ds* from 85 to 92 m with a security on the parasitic separation distance δX_{12} which permits us to lower the field in our electrostatic separator.

Acknowledgement

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References

[1] L. Keller, Zero degree extraction using an electrostatic separator, ILC Snowmass meeting (2005)
[2] E. Keil, Beam-Beam dynamics, CERN SL/94-78 (1994)
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