SIMULATING THE WIRE COMPENSATION OF LHC LONG-RANGE BEAM-BEAM EFFECTS

T.L. Rijoff, F. Zimmermann, CERN, Geneva, Switzerland

Abstract

The performance of the Large Hadron Collider (LHC) and its minimum crossing angle are limited by long-range beam-beam collisions. Wire compensators can mitigate part of the long-range effects. We perform simulations to explore the efficiency of the compensation at possible wire locations by examining the tune footprint and the dynamic aperture. Starting from the weak-strong simulation code BBTrack we developed a new Lyapunov calculation tool, which seems to better diagnose regular or chaotic particle behavior. We also developed faster ways to execute the simulation and the post-processing. These modifications have allowed us to study different wire positions (longitudinal and transverse), varying wire currents, several wire shapes, and a range of beam-beam crossing angles, in view of a prototype wire installation in the LHC foreseen for 2014/15. Our simulations demonstrate that the wire can provide a good compensation, including for reduced crossing angle. Among the benefits of an LHC wire compensator are a better overlap of colliding bunches, as well as the possibility of smaller β^* or higher beam current.

INTRODUCTION

To reach high energy and high luminosity it is important to compensate the negative effects due to the electromagnetic interactions between the two beams before and after the collision points, the so called beam-beam effects [1]. This possible limitation of the collider performance can be partially mitigated with a DC wire compensator [2]. A very good compensation should be obtained when the wire has a distance from the beam equal to the average long range distance (for nominal crossing angle this means 9.5 σ), and with a wire current that depends on the number of long range interactions $n_{\rm LR}$ according to the formula $I_{\rm opt} = n_{\rm LR} c e N_b / L_w$ (c speed of light and e elementary charge). If we consider 32 LR interactions ($n_{\rm LR}$) in total at one Interaction Point (IP), with 1.15×10^{11} particles per opposite bunch (N_b), and a wire length (L_w) of 1 m, we obtain $I_{\rm opt}$ = 176.8 A.

From the longitudinal point of view, the best compensation is obtained when the $\beta_x + \beta_y$ at the wire and when the betatron phase advance between the LR collision points and the wire is as small as possible. For the nominal LHC optics an optimal location has been found at 104.9 m from the IP [3], in the MAD optics this location carries the label "BBC" (Beam Beam Compensator).

For technical reasons we need to explore solutions different from the one indicated above: so (1) we analysed what happens moving the wire into the shadow of the collimator (for nominal crossing angle this means to 11 σ), (2) we checked what happens if we use the same electric current as at 9.5 σ (I=176.8 A) as when scaling the current quadratically (I = 237 A) (3) we tried different longitudinal wire locations: (4) we tested a modified optics [4].

We analyzed the following scenarios: Head On (HO): 2 head-on collisions at IPs1 and 5, Head On Long Range (HOLR): 2 HO collisions plus 16 LR collisions at each side of the IP1 and IP5, Beam Beam Compensator (BBC): HOLR plus a wire at 105 m after IP1 and IP5, Tertiary Collimator Target (TCT): HOLR plus a wire at 147 m before IP1 and IP5, TCT opt β: HOLR plus a wire at 150 m after IP1 and 147 m before IP5, TCT opt β: 2 HOLR plus a wire at 147 m before IP1 and 150 m after IP5 and Quadrupole 5 (Q5): HOLR plus a wire at 199 m after IP1 and IP5

We find that BBC offers the best compensation, but the simulated performance is promising also for TCT if we use the modified optics, which could be studied experimentally in the LHC from about 2015 onward, and for TCT opt β with nominal LHC optics.

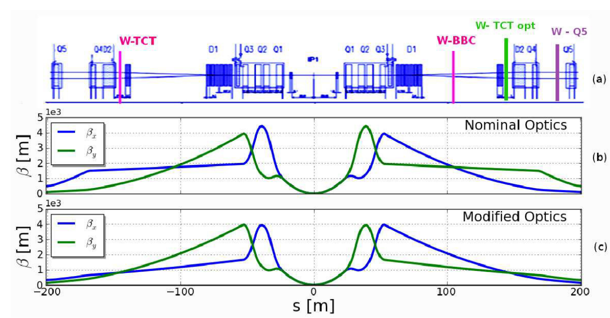

Figure 1: IP1: possible wire positions (row 1), β functions for LHC nominal optics (row 2) and modified optics (row 3)

For the most interesting cases we varied the crossing angle in the range [12,6.3] σ, and found that suitably placed LHC wire compensators should allow for a reduction of the crossing angle by the equivalent of at least 1-2 σ while maintaining the same stable region in phase space as for the larger crossing angle without compensator.

SIMULATION TOOLS

We used the weak-strong code BBTrack [5] to track the particles, and we developed new postprocessing tools to analyse tune footprints and particle stability [6].

Stability Analysis

We tracked each particle, together with a twin particle launched with a small transverse offset of 10^{-8} m , for at least 300,000 turns. To determine the stability of a particle trajectory, on each turn (j) a Lyapunov indicator, $\lambda[j]$, is computed from the time evolution of the normalized distance d in phase space between the two twin particles.

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Specifically, a particle is considered as unstable if $\lambda[j]$ exceeds a certain threshold value (taken to be equal to 3 in our tests). The original formula for $\lambda[j]$

$$\lambda[j]\ (\text{old}) = \frac{d_r[j] - d_r[0]}{2d_r[j/2]} \tag{1}$$

flags some stable particles as unstable, for example the first particle plotted in Fig. 2. We introduced the improved formula

$$\lambda[j](\text{new}) = \frac{\langle d_r[\frac{j}{2} : j]\rangle - \langle d_r[0 : \frac{j}{2}]\rangle}{\langle d_r[j/4 : 3j/4]\rangle}\ , \tag{2}$$

with $\langle d_r[m1 : m2]\rangle$ denoting the average value of d between turns $m1$ and $m2$. Using the new formula the top case in Fig. 2 is correctly identified as stable, the bottom case as unstable.

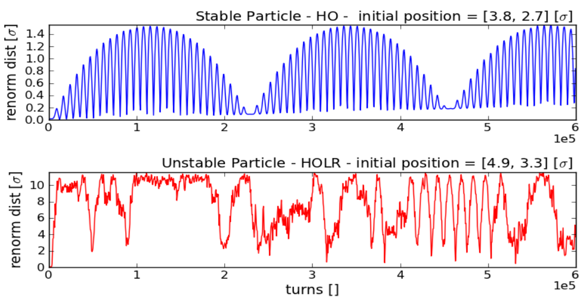

Figure 2: Normalized distance as a function of turn number for a stable (top) and an unstable trajectory (bottom) .

Figure 3 illustrates, for an example, that the stable region in amplitude space does not change when we further increase the number of turns. In the figure, the horizontal (vertical) axis refers to the horizontal (vertical) start amplitude in units of σ_x (σ_y). The color code indicates the number of turns after which an instability has been detected.

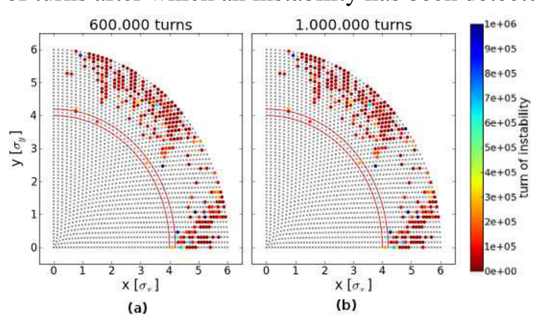

Figure 3: Particle stability for HOLR with a reduced crossing angle corresponding to a LR separation of 6.3σ, when tracking over 6×10^5 (left) or 10^6 turns (right).

Tune Footprint Analysis

We considered a particle distribution in [0,6.5] σ with more particles in [3,6.5] σ, since the long range collisions affect particles with larger amplitude. For each particle we recorded its position at IP1 for the first 50.000 turns and we calculated the tune taking the maximum of the real fast fourier transform (rfft) of positions as function of the turn number . We plotted the fractional part of the tune checking if we touched any resonance lines with order ≤ 9.

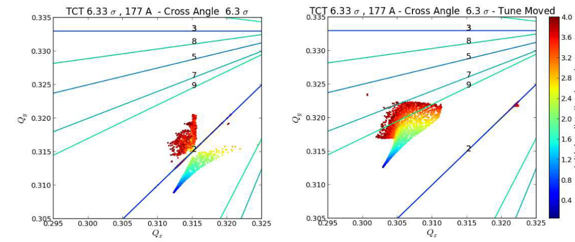

Figure 4: Tune footprint for TCT wire at 6.3σ with current 177 A if we suppose a reduced crossing angle corresponding to a LR separation of 6.3σ, without modification (left), and moving back the central tune (right)

In some cases, the central tune is too close to, or in the worst cases crosses, one of the resonance lines, causing instabilities. In these cases we moved the central tune back with a bbtrack feauture and the formula

$$\Delta Q_u = \pm\frac{r_0 I_w L_w \beta_u}{2\pi\gamma e c d_w^2} \tag{3}$$

where d_w is the wire distance and $-$ refers to the plane of crossing.

RESULTS

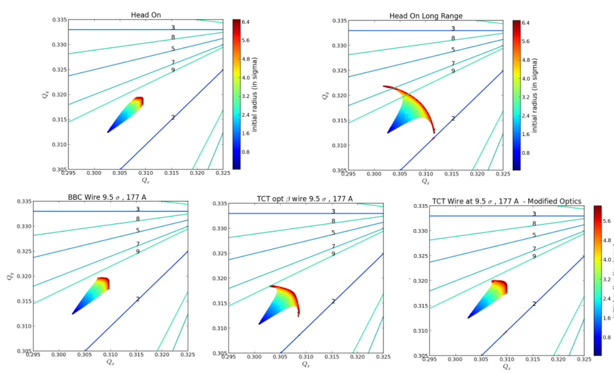

Figure 5: Tune footprint for HO (top left), HOLR (top right) wire compensator with current 177 A and transversal position 9.5 σ located at BBC (bottom left), TCT opt β (bottom center), TCT with modified optics (bottom right)

From the tune analysis we obtain the best results with a current of 177 A and a transversal position of 9.5σ. As visible in the Fig. 5 (bottom left), a wire located at BBC gives a tune footprint almost identical to the one obtained without the long range effects. Also a wire at the TCT location with modified position (bottom center) or optics (bottom right) give satisfactory results.

On the other hand, in the stability analysis (Fig. 6) the best results are obtained with a current of 237 A and a transversal position of 11σ. For example using a wire at BBC position we pass from 5.7% of unstable particles of HOLR tests (top right) to 0.5% of unstable particles if the wire is located at 11 σ and has a current of 237 A. For a transverse position of 9.5 σ and a current of 177 A we obtain 2.2% of unstable particles, and similar results for the wire at TCT with opt β or with modified optics (in both these cases we have 2.4% of unstable particles).

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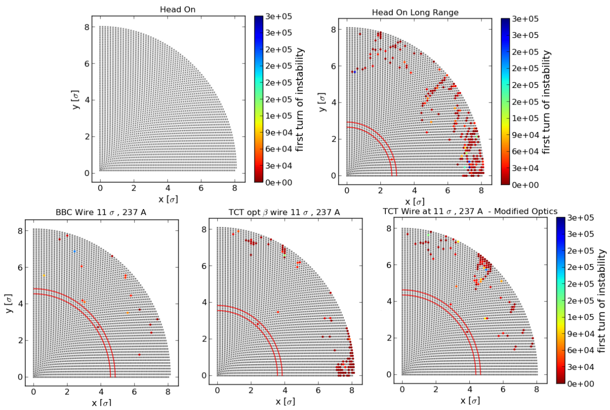

Figure 6: Particle stability for HO (top left), HOLR (top right) wire compensator with current 237 A and transversal position 11 σ located at BBC (bottom left), TCT opt β (bottom center), TCT with modified optics (bottom right)

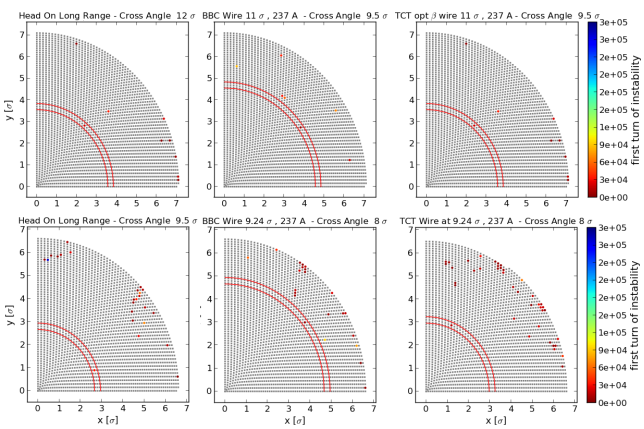

Figure 7: Particle stability: top left: HOLR crossing angle of 12 σ; crossing angle of 9.5 σ, wire at 11 σ, with a current of 237 A at BBC position (top center) and at TCT opt β position (top right). bottom left: HOLR crossing angle of 9.5 σ; crossing angle of 8 σ a wire at 9.24 σ, with a current of 237 A at BBC position with nominal optics (bottom center) and at TCT position with modified optics (bottom right)

Comparing the stability plots for different crossing angles (Fig.: 7) we notice that suitable wire compensators allow us to reduce the crossing angle by at least 1-2 σ maintaining the same stable region in phase space. For example, the stable region for a nominal crossing angle (9.5 σ) with wire compensators at BBC or TCT opt β is comparable to the stable region if the two beams have an average separation of 12 σ (first row). In a similar manner second row of Fig. 7 shows that with a wire compensator at the BBC with nominal optics or at the TCT location with modified optics we can reduce the crossing angle to 8 σ and obtain the same stable region as for the HOLR with a crossing angle of 9.5 σ.

If the beam beam average distance is reduced to 6.3 σ the long range beam beam effects become more dangerous and for several particles the tune crosses a resonance line of order 2 as illustrated in Fig. 8 (top). The bottom pictures line show how wire compensators can correct the long range effect also at this crossing angle.

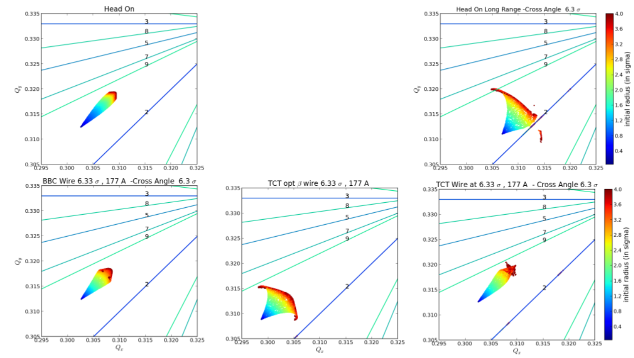

Figure 8: Tune footprint crossing angle 6.3 σ: top: HOLR. bottom: Wire at 6.33 σ with a current of 177 A. bottom left: at BBC, bottom center: at TCT opt β, bottom right: at TCT with modified optics.

CONCLUSIONS

We analyzed the possible compensation of long range beam beam effect in the LHC through an electric wire. We based our work on the bbtrack code [5]. We noticed that in some cases the stability analysis flags some stable particles as unstable. Therefore we developed a new way to calculate the Lyapunov coefficient. We verified that this automatic method is consistent with the identification based on direct data inspection and the results are stable when we increase the number of turns. With some Python scripts to speed up the input file generation, tracking execution and postprocessing analysis we explored the behaviour of the wire compensator for various longitudinal and transversal positions, with different currents, two different optics and of crossing angle. We saw that a wire at BBC location provides the best compensation and allows reducing the crossing angle by 1-2 σ, maintaining the same stable region in phase space. Compensation effects are also promising for the TCT location and the modified optics, as well as for a modified TCT location (TCT opt β) with the nominal LHC optics.

REFERENCES

[1] W. Chou, D. Ritson, Proc. PAC97, Vancouver, p. 113; Y. Papaphilippou, F. Zimmermann, PRST-AB 2, 104001 (1999); M. Albert et al, CERN-ATS-Note-2011-058 MD

[2] J.-P. Koutchouk, PAC Proc. PAC2001, Chicago, p. 1681

[3] U.Dorda “Compensation of long-range beam-beam interaction at the CERN LHC” (May, 2008)

[4] S. Fartoukh private comunications (2012)

[5] U. Dorda, BBTrack *http://ab-abp-bbtrack.web.cern.ch*

[6] T. Rijoff, “Testing long range beam-beam compensation for the LHC luminosity upgrade” (July, 2012)

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