SIMULATION STUDIES FOR THE LHC LONG-RANGE BEAM-BEAM COMPENSATORS *

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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 and may allow for smaller crossing angles, smaller β^*, or higher beam intensity. A prototype long-range wire compensator should be installed in the LHC by 2014/15. We report simulation studies examining and comparing the efficiency of the wire compensation, in terms of tune footprint or dynamic aperture, at various candidate locations, with different wire shapes, and for varying transverse distance from the beam.

INTRODUCTION

The two counter-rotating proton beams of the LHC do not only collide head-on (HO) at the two main interaction points (IPs), but also experience about 16 long-range (LR) encounters on either side of each IP. These LR collisions (up to about 128 in total) are expected to limit the LHC performance [1]. Their effect can be compensated, at least partially, by an electric wire [2], installed near the IP at a place where the two beams are already separated and with a transverse distance (normalized to the beam size) about equal to the average beam-beam distance of the LR collisions. The optimum wire current is then given by $I_{\rm opt} = n_{\rm LR} c e N_b / L_w$ (with c speed of light and e elementary charge). Considering 32 LR interactions ($n_{\rm LR}$) in total at one IP, with 1.15×10^{11} particles per opposite bunch (N_b), and a wire length (L_w) of 1 m, we have $I_{\rm opt} = 176.8$ A. The transverse position should be equal to the average distance at the long-range collisions. For the nominal LHC this corresponds to 9.5 σ (with $\gamma\epsilon = 3.75$ μm). In view of machine protection it may prove necessary to increase the transverse distance of the wire from the beam to be larger than 9.5σ.

The best compensation is obtained when the β functions have the same value in the transverse planes, and when the betatron phase advance between the LR collision points and the wire is as small as possible [3]. For the nominal LHC optics an optimal location has been found at 104.9 m from the IP [2], which has been reserved for a future wire compensator [4]. In the MAD optics this location carries the label "BBC" (Beam Beam Compensator).

The construction of a prototype LHC wire compensator is planned for installation in 2014/15 and subsequent beam tests. For various reasons this initial prototype cannot be installed at the BBC location, but it should be located further away from the IP (-147 m, at the tertiary collimator jaw, the TCT).

The two locations – BBC and TCT – are shown in Fig. 1 along with the nominal LHC optics and with a modified optics [5]. The latter optics, based on the ATS scheme [6], has been taylored so as to give optimized compensator performance with a wire placed at the TCT, e.g. for future machine studies. In other words the modified optics makes the TCT location "look like" the BBC location for the nominal optics, in terms of the ratio of beta functions and in terms of phase advance (see Table 1).

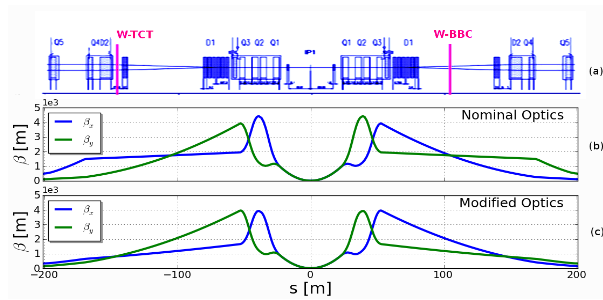

Figure 1: Wire locations (top), and β functions for the nominal (center) and the modified optics (bottom).

Table 1: Optics parameters at the BBC location in the nominal optics ($\beta^* = 0.55$ m) and at the TCT with the modified optics ($\beta^* = 0.60$ m).

position	IP	IP dist [m]	β_x [m]	β_y [m]
BBC	IP1	104.9	1738.1	1734.8
	IP5	104.9	1739.2	1734.9
TCT	IP1	-146.9	801.0	802.5
	IP5	-147.3	798.0	794.1

We examined the performance for two configurations: nominal optics with a wire at BBC, and modified optics with a wire at the TCT, comparing the following scenarios: (1) 2 head-on collisions at IPs1 and 5 for either optics (HO), (2) 2 HO collisions plus 16 LR collisions at each side of the IP1 and IP5 (HOLR), (3) HOLR plus a wire at 105 m after IP1 and IP5 for the nominal optics (BBC), and (4) HOLR plus a wire at 147 m before IP1 and IP5 (TCT). In addition to the canonical transverse distance of 9.5σ, we also considered an increased distance of 11σ, obtaining in some cases better results, especially if the current was scaled quadratically with the distance (to $I = 237$ A).

SIMULATION TOOLS

All simulations were performed with the weak-strong code BBTrack [7]. New postprocessing tools were used to analyse tune footprints and particle stability [8].

Each particle, together with a twin particle launched with a small transverse offset of 10^{-8} m , is tracked for at least

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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. 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. Introducing 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 $m2$, the top case in Fig. 2 is correctly identified as stable, the bottom case as unstable.

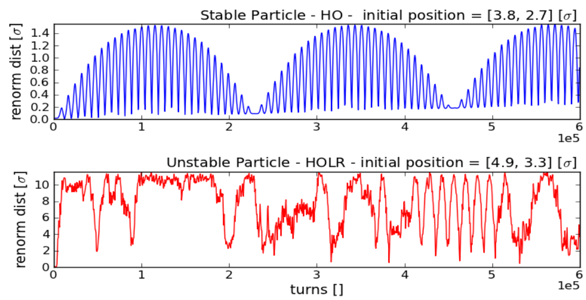

Figure 2: Normalized distance as a function of turn number for a stable (top) and an unstable trajectory (bottom) .

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.

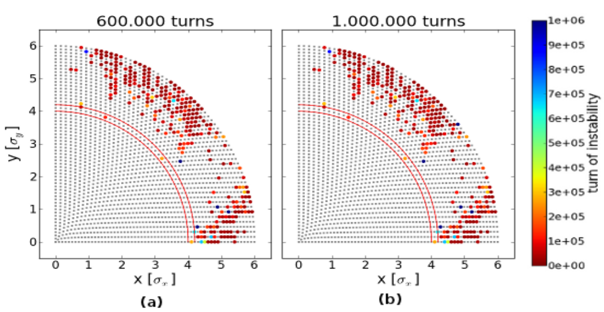

Figure 3: Particle stability for HOLR with a reduced crossing angle corresponding to a LR separation of 6.3σ, when tracking over 6×10^5 (left) or 10^6 turns (right).

SIMULATION RESULTS

Nominal LHC Optics

If the wire is put at the BBC position with a current of 177 A and a transverse distance of 9.5 σ from the beam we find a tune footprint for particles between 0 and 6.5σ which is almost identical to the one obtained for HO; compare Fig. 4 (top left) with (bottom left). In particular the tunes do not cross any resonance lines of order smaller than 10. Also at a larger distance of 11 σ the HOLR effect on the footprint can be well compensated when using the quadratically scaled wire current of 237 A (the bottom right picture). This latter case also yields the best result for the percentage of unstable particle in the interval between 0 and 9σ: only 3 % of particles is found to be unstable in our tracking, compared with 10% for the HOLR case without any compensation. For more details on the stability see Fig. 5.

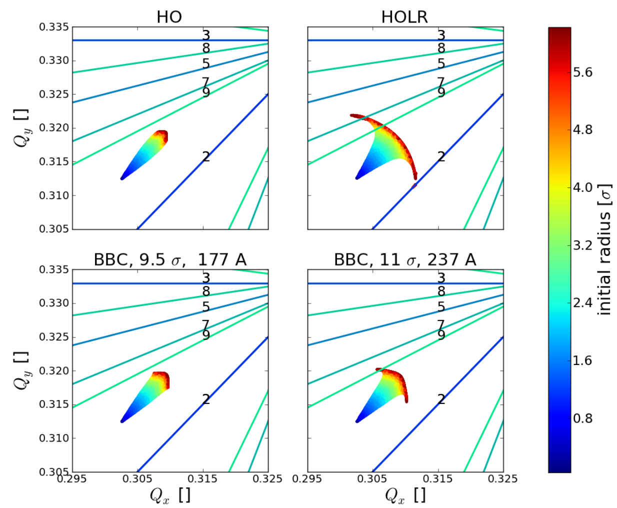

Figure 4: Tune footprint for the nominal LHC optics and crossing angle corresponding to a 9.5σ separation, with HO only (top left) HOLR (top right), BBC wire at 9.5σ (bottom left) and BBC wire at 11σ (bottom right).

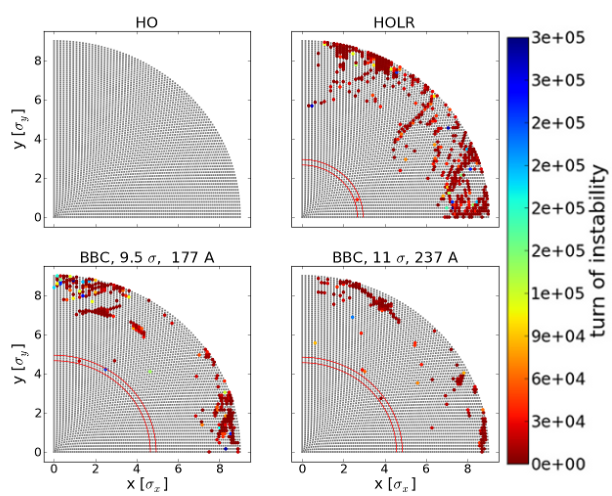

Figure 5: Particle stability for the nominal LHC optics and a crossing angle corresponding to 9.5σ separation considering the same four cases as in Fig. 4.

Demonstration experiment

At the TCT location, where a prototype wire compensator can be installed for a demonstration experiments, the beta functions β_x and β_y differ by almost a factor of 3. Dedicated demonstration studies could, however, be performed with the modified ATS-like optics, for which $\beta_{x,y} \approx 800$ m. Figure 6 shows that, with this optics,

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the tune footprints resemble those obtained for the nominal LHC optics and the BBC wire position (Fig. 4), where the best compensation results are obtained for a transverse wire distance of 11σ (the two bottom pictures). With a wire current of 177 A the percentage of unstable particles is about half the one for HOLR without compensation; (see Fig. 7).

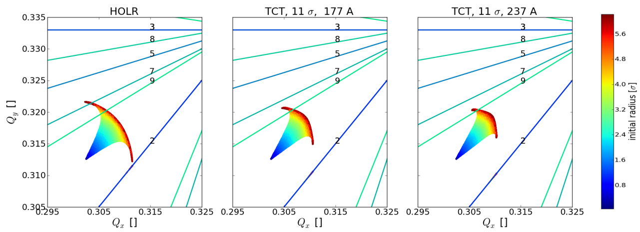

Figure 6: Tune footprints for the modified LHC optics and a crossing angle corresponding to 9.5σ separation.

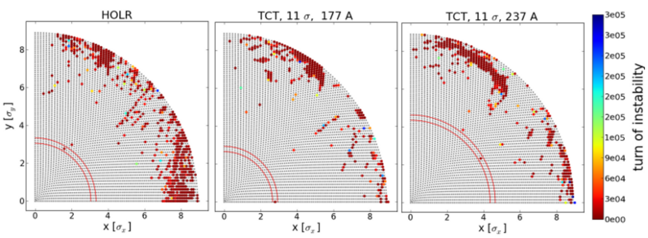

Figure 7: Particle stability for the modified LHC optics and a crossing angle corresponding to 9.5σ separation.

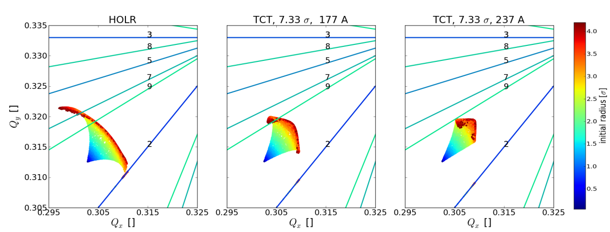

Figure 8: Tune footprints for the modified LHC optics and a reduced crossing angle corresponding to 6.3σ separation.

Reducing the crossing angle by 2/3 to a separation of 6.3σ, the HOLR effects become more significant as it is shown in Fig. 8. The number of unstable particles increases to almost twice the value for the nominal crossing angle ($9.5\ \sigma$). A current of 237 A provides the best results both from the footprint and the stability points of view (Fig. 9). For this lower crossing angle, we removed from the analysis all those particles that otherwise would touch the wire, now located at $7.3\ \sigma$ (scaled down from 11σ).

Wire shape

All the simulations reported above were performed with a pencil-like wire. The actual wire will have a finite transverse size of the order of 1σ and, in order to be embedded in a collimator jaw, it might not even be round. The consequences of using a square-rod wire with 1-mm width have been investigated by simulations, yielding essentially the same results as for the pencil wire. In some regards, the more realistic finite square wire may even provide an

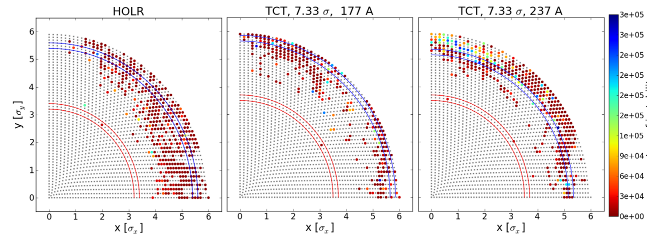

Figure 9: Particle stability for modified LHC optics and a reduced crossing angle corresponding to 6.3σ separation.

improvement, e.g. the percentage of unstable particles decreases from 6% for a pencil-like wire to 4% for the square-rod wire. However, the tune footprint looks slightly better for the case of the pencil wire (see Fig. 10).

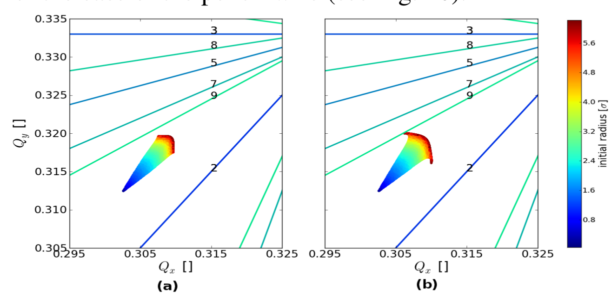

Figure 10: Tune footprints for the nominal optics with a BBC wire, for a pencil (left) and a square-rod wire (right).

CONCLUSIONS

Several configurations have been examined of LHC long-range wire compensation, both for the nominal LHC and for an initial demonstration experiment with a different wire location and modified optics. The best compensation results are obtained with a wire located at the nominal BBC locations with a transversal position of 9.5σ or 11σ and a current of 177 A. Our simulations show that the wire can give a good compensation also when we reduce the crossing angle. Suitably placed LHC wire compensators should allow for a reduction of the crossing angle by the equivalent of at least 1-2σ while maintaining the same stable region in phase space, or, alternatively, for a substantial increase in beam current (e.g. by a factor of 2) at constant crossing angle. Compensation effects are also predicted for the TCT location and the modified optics, which could be studied experimentally in the LHC from about 2015 onward. The exact shape of the wire (round or square) has little effect on the compensation quality.

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