SIMULATION OF LHC LONG-RANGE BEAM-BEAM COMPENSATION WITH DC AND PULSED WIRES

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Abstract

We describe computer simulations of long-range beam-beam interactions (LR-BBI) and a potential wire compensation for the LHC.

After a short motivation for these studies, we present tune footprints simulated for various types of perturbation. The following section states reasons why a wire-compensation cannot work perfectly and it explores the compensation effectiveness for nominal and Pacman bunches. Then, one example of the difficulties in simulation is presented, namely the strong sensitivity to the presence of other nonlinearities. Next, the challenging demands on the current supply for a pulsed-wire option are discussed. Finally, a short summary of promising results in the SPS two-wire beam experiments is given.

MOTIVATION

In the nominal LHC scheme (with a full crossing angle θ_c of about 300 μrad) the nonlinear forces caused by the LR-BBI (average beam-beam separation d=9.5σ) result in particle loss and emittance growth, which limit the beam lifetime and the ultimate luminosity. Attempting to reduce its strength by increasing the crossing angle is not possible as this would result in unacceptable geometrical luminosity losses; neither would it be compatible with the existing aperture of the final-triplet magnets. As the deflecting field caused by the opposite beam is - within a given limit - similar to the one of a current-carrying wire, it seems reasonable to study the effectiveness of a wire compensation [1].

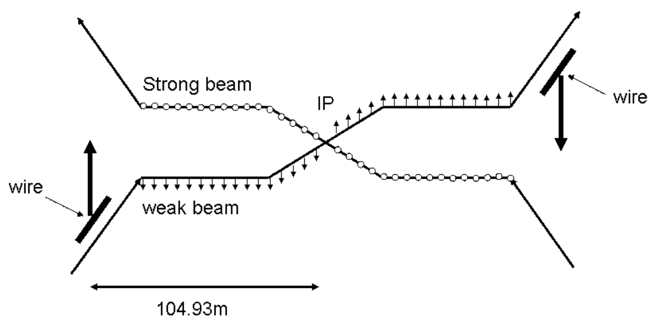

Figure 1: The compensation wires will be positioned 104.93m from IP1 and IP5, where the beams are already in their separated beam-pipes [1]. The arrows indicate the strength and direction of the force due to the LR-BB and the wire. The two wires shown compensate the force exerted by one ‘strong’ beam on the other ‘weak’ beam. The equivalent set of two wire compensators will be installed for the second beam, for which the roles of strong and weak beam are interchanged.

One of the possible LHC-upgrade scenarios foresees the installation of wires in the beam pipes parallel to the beam next to the two high-luminosity interaction points (IPs) at the CMS & ATLAS detectors (Fig. 1).

VARIOUS TYPES OF PERTURBATIONS

For nominal LHC parameters (see Table 1), bunches in the centre of a bunch train (nominal bunches) encounter 60 LR-BBI around the two high-luminosity IPs, at which the two colliding beams are crossed in the horizontal and vertical plane, respectively. BBTrack [2], a weak-strong tracking code similar to the one described in [3], was used for calculating the tune footprint of the LHC due to LR-BBI (Figure 8).

Parameter	**Symbol**	**value**
No. bunches	n_b	2808
Protons per bunch	N_b	$1.15\text{x}10^{11}$
Bunch Spacing	t_s	25 ns
Crossing angle	Θ_c	285 μrad
Beta function at IP	β^*	0.55 m

Table 1: Nominal LHC parameters with alternating planes of crossing at IP1 and IP5.

The linear tune shift can be estimated from formula (1), which highlights its inverse square dependence on the beam-beam separation.

$$\Delta Q = \pm 2 n_{par} \frac{N_b r_p}{4\pi\gamma\varepsilon\left(\frac{d}{\sigma}\right)^2} \qquad (1)$$

where n_{par} denotes the number of parasitic collisions, N_b the bunch population, $(\gamma\varepsilon)$ the normalized transverse emittance, (d/σ) the beam-beam separation in units of the rms beam size and r_p the classical proton radius.

In the nominal LHC, the linear tune shift induced by the long-range collisions is cancelled between the two main IPs by the alternating crossing. However, this cancellation is no longer true at higher order. In Fig. 8, the large tune shift of the higher amplitude particles (red) can clearly be seen and resonance-lines be identified. In addition, one has to take into account the tune spread due to the desired head-on collisions (HO) at the primary IPs, which affect the small-amplitude particles. Figure 9 shows a footprint representing the combined effect of long-range and head-on collisions (LR & HO). Here the tune shift of the small-amplitude particles arises mainly from the HO, while the large-amplitude particles are affected by the long-range collisions in similar way as in Fig. 8. Bunches at the ends of a bunch-train encounter less LR-BBI (due to gaps in the bunch pattern, e.g., the abort gap, there is no opposing bunch at some of the LR-BBI points) and they are called Pacman bunches. The very last one ("extreme Pacman") encounters no LR-BB at all on one side of the IP, and, therefore, it exhibits only half the long-range tune spread. Nearly half of the bunches are Pacman ones and need a special compensation treatment. The footprint for the extreme Pacman case is displayed in Fig. 10.

WIRE COMPENSATION

In the hypothetical case of no LR-interaction, the wire itself would be a strong source of nonlinearity and cause a tune spread which can be seen in Fig. 11. The sign of the wire current is chosen so as to cause a tune-shift in the direction opposite to the LR-case.

Limitations of compensation effectiveness

For the following reasons the wire compensation will not work perfectly:

- The average phase advance between the LR-IPs and the wire is 2.6º.
- The beam-beam spacing varies between the different LR-IPs (minimum separation: 7σ, maximum separation: 13 σ, Fig. 2).
- The LR-force is similar but not identical to the one caused by the wire.
- The real beam-shape is unknown; it is modelled as Gaussian.
- The wire may have to be positioned in the shadow of the collimators at amplitudes larger than 11 σ, instead of at the optimal distance of 9.5σ.

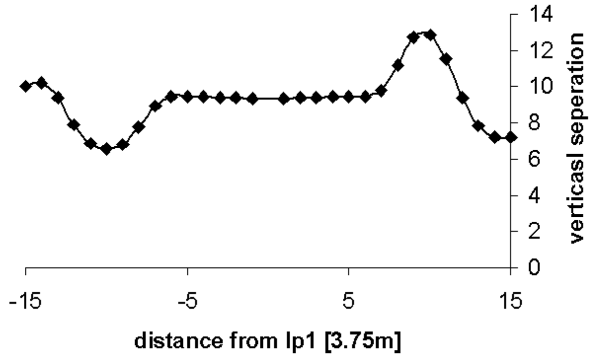

Figure 2: The beam-beam separation varies between 7σ and 13σ. This variation is one of the reasons why the compensation with a single wire cannot work perfectly.

Wire parameters

In order to be able to install the wires in an LHC upgrade, 3m of space is reserved on both sides 104 m from the two high-luminosity IPs, where the beams are in their separated vacuum pipes. Within limits the required wire current is inversely proportional to the wire length. In the simulation, a wire length of 1 m is chosen. For the optimal beam wire distance, which nearly equals the average beam-beam-separation (9.5σ), the optimal current is given by Eq. (2).

$$I_w = \frac{-4\pi(B\rho)N_b r_p n_{par}}{\mu_0 \gamma l_w} = 81A \qquad (2)$$

Tune-spread compensation

Figure 12 demonstrates that the wire is capable of compensating most of the tune spread induced by the LR. In fact, the tune-footprint is almost reduced to the one of HO-collisions only. A similar simulation for an extreme Pacman bunch reveals that the application of the same wire current leads to an overcompensation (Fig. 13). In this case the total extent of the tune footprint is about constant, but the shape of the footprint changes due to the compensator. As is shown in Fig. 14, an adapted (reduced) wire-current would allow a much better compensation for this case. Therefore, the implementation of a pulsed compensator appears worth some effort.

DEMANDS ON PULSED-WIRE CURRENT SUPPLY

As we have argued above, it is of interest to adapt the wire current for each bunch. The sequence of nominal and Pacman bunches is defined by the bunch pattern. Simulations show that the compensation effectiveness is not too sensitive to the exact value of the wire current, but that, on the other hand, small turn-to-turn variations in this current cause an emittance blow up which, as expected from theory, depends quadratically on the noise amplitude (Fig. 3). For example, according to the simulation, a jitter amplitude of 4 mA results in 10% emittance growth over 20 hours. Due to radiation issues in the LHC tunnel, the current generator cannot be placed right next to the wire, but instead a transmission line with a minimum length of 100 m will be required. The design of the current generator must then take into account delay times and reflections. The required power should be kept as low as possible, as only the magnetic field is relevant. Table 2 summarizes the demands on the pulsing unit.

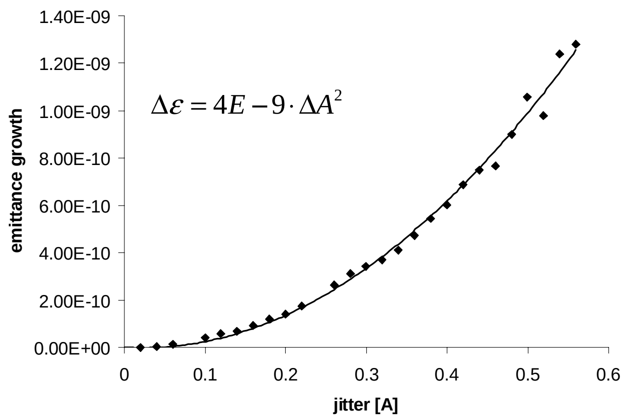

Figure 3: The emittance growth increases with the square of the jitter-amplitude.

Parameter	value
Maximal current	120 A
Total ramp up/down time from zero	374.25 ns
Length of maximal excitation	1422.15 ns
Length of minimal excitation	573.85 ns
Average pulse rate	439 kHz
Turn-to-turn amplitude stability (rel.)	0.5×10^{-4}
Turn-to-turn timing stability	0.02 ns

Table 2: The demands on the power supply in case of a pulsed wire option.

INTERPLAY WITH OTHER NONLINEARITIES

Unfortunately the LR-BBI is not the only source of nonlinearities in the machine. In combination with the LR-interaction, other, taken individually comparably harmless, nonlinearities cause the dynamical aperture (DA) to shrink. As a test case the influence of a single sextupole was studied and the capability of the wire to compensate the LR-BB is such a case was investigated. The sextupole strength was adjusted so that the sextupole field alone resulted in a stability border of 40σ. In combination with the LR-BBI this seemingly small effect causes the overall DA to collapse from 7.5σ with LR-BB alone to 2.5σ. Figure 4 shows the effectiveness of the wire compensation as a function of the wire current. It can be seen that once again the compensation is quite effective and that the analytically computed value of the optimum wire current (81A) well matches the simulated value. These results stress the importance of including all – even seemingly negligible - nonlinearities of the machine in the simulations.

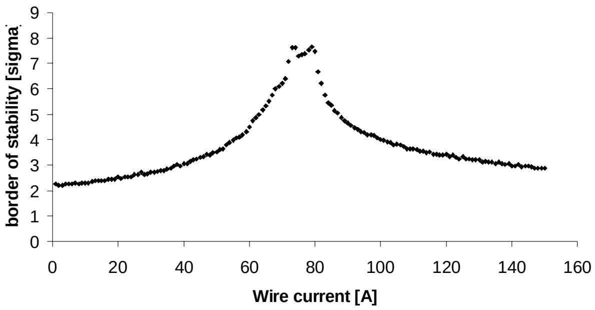

Figure 4: Seemingly negligible additional nonlinearities reduce in combination with LR-BBI the dynamical aperture significantly. Once again the wire compensation is capable to improve stability.

SPS EXPERIMENTS

Two wires were installed in the SPS in order to allow experiments [4,5]. The first wire is meant to excite the beam, while the second one, 2.6º further downstream, was used to test its capability of compensating for the distortions introduced by the first one. Figure 15 shows the beam lifetime in the unperturbed case (no wire powered), the perturbed case (wire 1 current carrying) and the compensated case (both wires on) as a function of the vertical tune. It can clearly be seen, that the compensation works fine within a given tune range. We note that the beam lifetime was rather short even without wire compensation, under the conditions of the SPS experiment. Figure 5 presents the simulated dependence of the dynamic aperture on the current of the second wire. The dependence is rather flat around the optimal point.

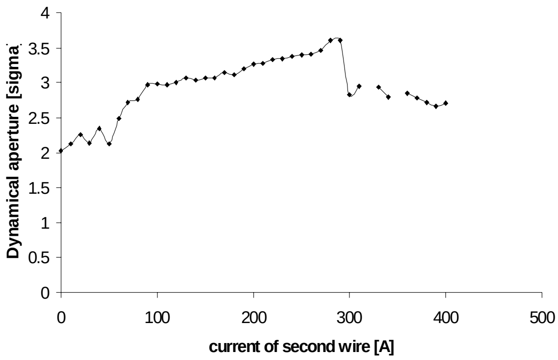

Figure 5: The compensation does not require an exact matching of the wire currents in the SPS compensation experiments.

As the LR-BBI in the LHC occur at different beam-separation distances it is of great importance to study the dependence on this parameter. Figure 6 shows the fortunately weak (simulated) dependence. This is consistent with the LHC-simulations, which show a good compensation capability of one wire placed at a fixed transverse position for 15 LR-BB interactions taking place at different *d*-values.

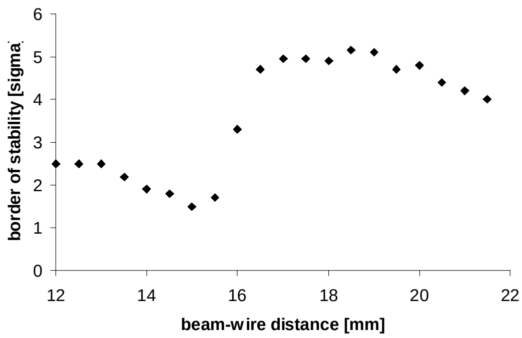

Figure 6: Fortunately, for a large range of beam-wire distances the compensation works almost perfectly.

The border of stability is calculated with the help of the Liaponov-exponent, which is a sensitive criterion for chaos detection. The Liaponov exponent characterizes the evolution of the betatron-phase difference between two initially very close particles. Figure 7 shows the evolution of the phase distance with the number of turns (=time) for

4 particle-pairs launched with increasing amplitudes. While the linear phase increase for the low-amplitude particle-pairs exhibits only the regular detuning with amplitude, the onset of an exponential increase at larger amplitude is characteristic of chaotic behaviour.

In Fig. 16 red regions indicate chaotic regions, while blue ones show regular behaviour during the first 300.000 turns tracked.

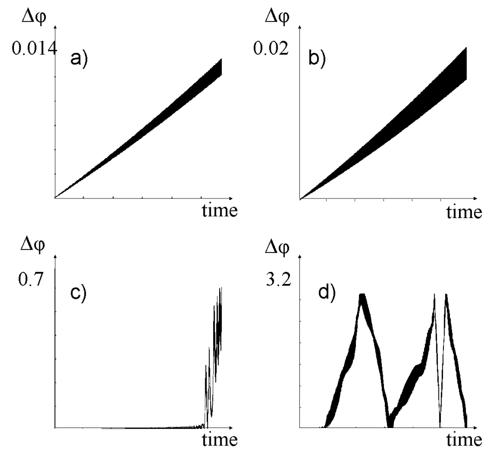

Figure 7: The time evolution of the phase distance between particle pairs for particles with increasing (a-d) initial amplitude. The onset of exponential growth indicates chaos and a non-zero Liaponov exponent.

SUMMARY

The proposed wire system seems to be capable of compensating the effect of the long-range beam-beam interactions in the LHC quite well, even, or especially, in the case that other sources of nonlinearities are also present. As almost half of the LHC bunches are Pacman ones, requiring a different wire current, the use of a pulsed wire seems strongly recommended. However, the demands on the current supply for such a device appear challenging. The tight tolerance on the turn-to-turn stability, which is equivalent to a high timing precision, is presently considered as a primary obstacle. The promising results from SPS two-wire experiments encourage a continuation of these studies.

ACKNOWLEDGEMENTS

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[5] F. Zimmermann and U. Dorda, "Progress of Beam-Beam Compensation Schemes," Proc. CARE-HHH-APD Workshop on Scenarios for the LHC Luminosity Upgrade (LHC-LUMI-05), Arcidosso, Italy, 2005.

ADDITIONAL FIGURES

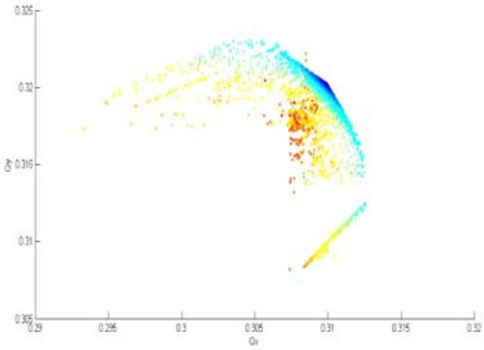

Figure 8: LHC - Tune footprint (0-10 σ) due to the LR-BB interaction (blue=low /red =high amplitude particles).

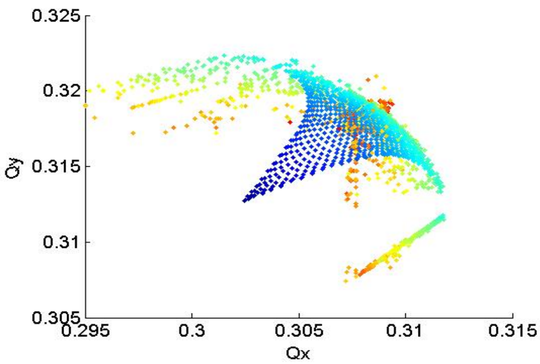

Figure 9: Tune footprint of LR and HO – collision.

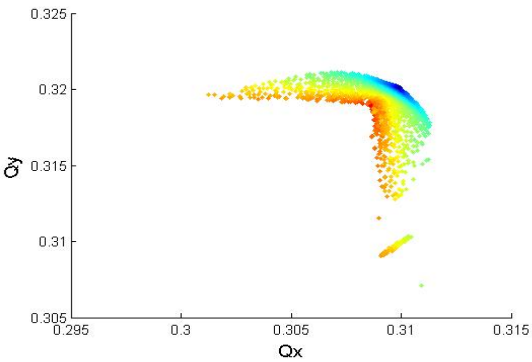

Figure 10: Pacman bunches encounter less LR-BB and therefore show less tune spread.

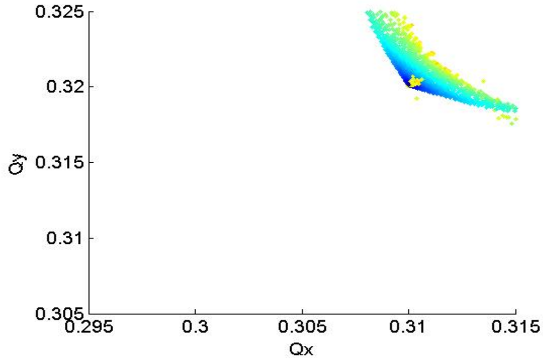

Figure 11: The tune spread due to the wire is directed in the opposite direction.

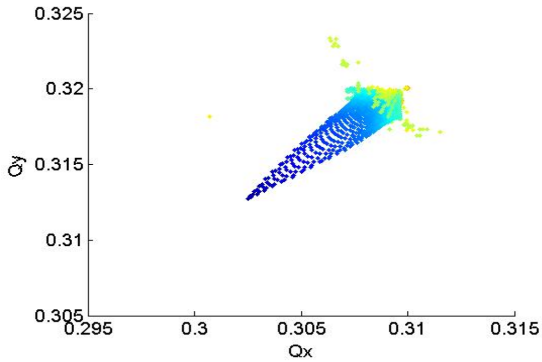

Figure 12: The wire is capable to compensate almost completely for the LR-BB. The tune footprint is reduced to the HO case.

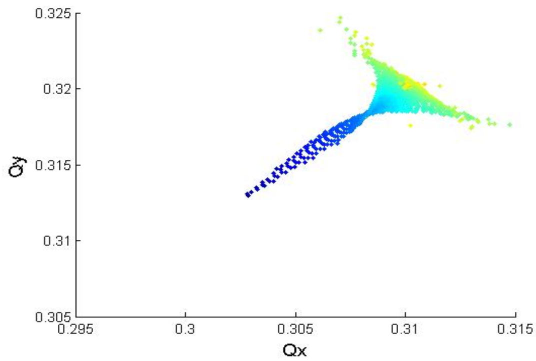

Figure 13: The nominal wire current overcompensates the tune spread in the Pacman case.

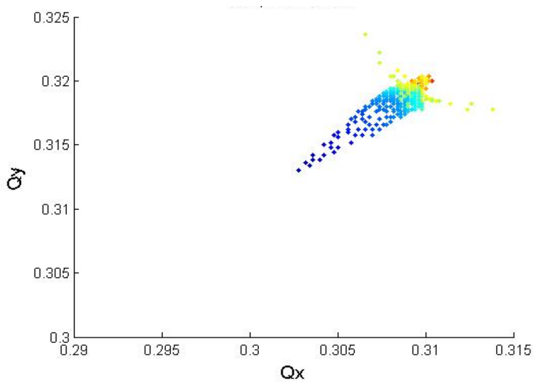

Figure 14: Adjusting the wire current allows good compensation also for the Pacman bunches.

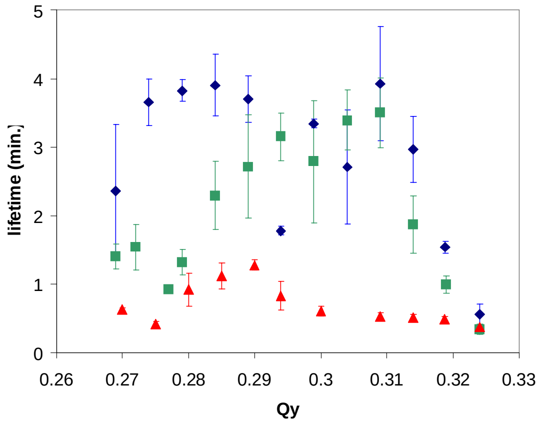

Figure 15: Experiments in the SPS nourish the confidence in the wire-compensation. The second wire is capable to compensate for the distortions caused by the first one. (Blue: no distortion; red: one wire only; green: both wires excited)

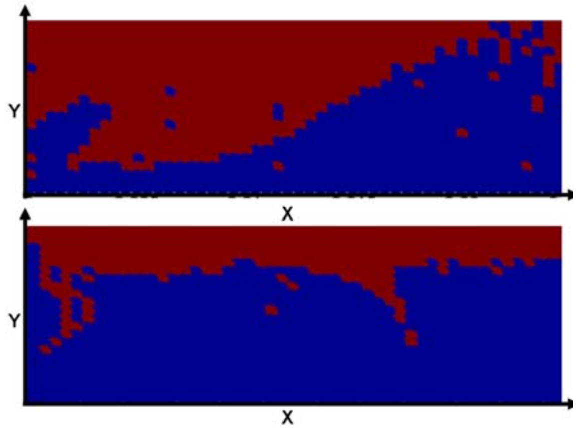

Figure 16: The stable (blue) and unstable (red) regions (0-10mm, wire at y=19mm) in the one-wire (top) and two-wire case (bottom).