LHC BEAM-BEAM COMPENSATION USING WIRES AND ELECTRON LENSES*

Ulrich Dorda, Frank Zimmermann (CERN, Geneva)
Wolfram Fischer (BNL, Long Island, New York), Vladimir Shiltsev (Fermilab, Illinois)

Abstract

We present weak-strong simulation results for a possible application of current-carrying wires and electron lenses to compensate the LHC long-range and head-on beam-beam interaction, respectively, for nominal and PACMAN bunches. We show that these measures have the potential to considerably increase the beam-beam limit, allowing for a corresponding increase in peak luminosity

INTRODUCTION

Already in the nominal LHC ($\beta^* = 55$ cm) with an average beam-beam separation of $d = 9.5\sigma$, the nonlinear forces caused by the long-range beam-beam interaction (LRBBI) will cause emittance blow up and limit the accelerator performance. In this paper we present weak-strong simulation results that demonstrate the benefit of a wire compensation (Figure (a)) for the nominal LHC but an even increased need for, together with more stringent performance requirements, for the proposed upgrade scenarios [2]. Figure (b) shows the normalized beam-beam separation for the nominal and the two available upgrade optics. All upgrade scenarios feature a larger number of LRBB encounters at reduced beam-beam separation. Compensating the head-on collision (HOC) by an electron lens could further boost the collider performance, as the HO affects the bunch core and drives particles to higher amplitudes at which point the LRBBI takes over and extracts these particles. All simulations reported in this paper were performed with the weak-strong tracking code BBTrack [4] considering the LHC upgrade case with collisions in CMS and Atlas only. The dynamic aperture (DA) is defined by the Lyapunov criterion computed for 300,000 turns. In the studies for the nominal LHC optics, the nominal triplet errors are also included.

WIRE COMPENSATION

Nominal LHC optics

The wire compensator should be placed at a location with symmetric β functions in both planes and with as little phase advance from the LRBB interaction-points (IPs) as possible. In the nominal LHC the wire should therefore be positioned at $s = \pm 105$ m from each IP ($\beta_{wire} \approx 1800$ m)

* We acknowledge the support of the European Community-Research Infrastructure Initiative under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395).

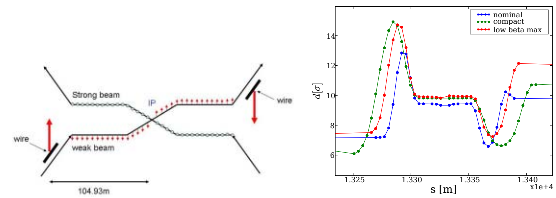

Figure 1: Left: locations and compensation principle of the proposed LHC wire compensators. Right: long-range beam-beam encounters at IP5 for the nominal LHC optics ($\beta^* = 0.55$ m) and for two of the upgrade scenarios ($\beta^* = 0.25$ m).

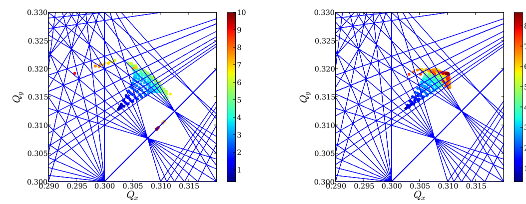

Figure 2: Tune footprint for the nominal LHC without (left) and with wire compensation (right). The color encodes the initial particle amplitudes.

[3]. In order to compensate for the 15 LRBBIs at an average separation of 9.5σ one has to position the wire compensator at the same normalized distance and excite it with a current of 81 Am [3]. The footprints in Fig. 2 show the almost perfect compensation of the LR tune spread as only the tune spread of the low amplitude particles due to the HOC remains. It should be possible to position the wire at the optimal beam-wire separation of 9.5σ, as the secondary collimators (set at 7σ) should provide sufficient protection. Fortunately the compensation is not very sensitive to the beam-wire separation, e.g., placing them at a higher d does not significantly decrease the DA, as is illustrated in Fig. 3. Figure 4 illustrates that the wire compensation improves the DA for almost any phase advance between the two IPs. In these simulations the total tune was kept constant. The sensitivity of the compensated and uncompensated DA to the betatron tunes was explored earlier in Ref. [5].

PACMAN bunches

PACMAN bunches are bunches at the end of a bunch train, that experience a reduced number of LRBBIs (in the extreme case no LRBBI on one side of the IP). Figure 5 shows that a wire compensation optimized for the nominal bunches would overcompensate the extreme PACMAN bunch. In order to also improve the stability of these parti-

1-4244-0917-9/07/$25.00 ©2007 IEEE

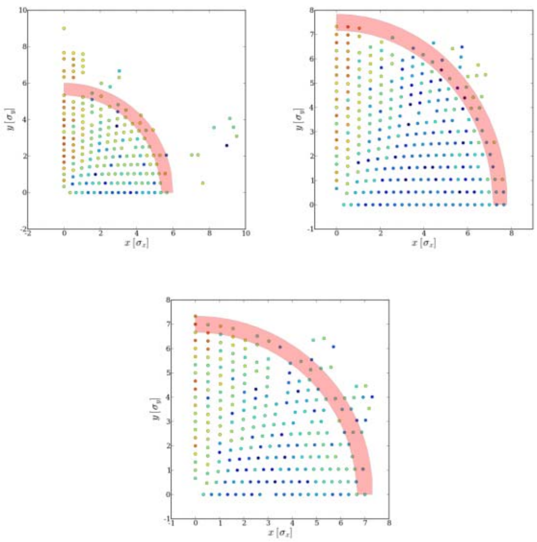

Figure 3: Dynamic aperture and particle stability as a function of horizontal and vertical start amplitudes for the nominal case (top left), wire compensation at 9.5σ (top right), and wire compensation at 11σ (bottom). The color encodes the strength of tune diffusion (same color code in all plots, $-2 \rightarrow -14$). Only stable particles are shown and the red transparent circle indicates the DA. It can be seen that the wire does not only increase the DA significantly but also improves the dynamics of low-amplitude particles.

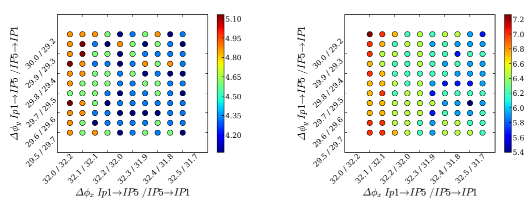

Figure 4: Phase-advance scan between IP1 and IP5 without (left) and with wire compensation (right) for a constant overall tune.

cles, one could try to find a compromise between the nominal and the PACMAN bunches as suggested by Fig. 6 (a). Alternatively, to archive the maximal possible gain, one could consider of a pulsed-current supply whose excitation mimics the bunch pattern. This idea faces a few technological challenges: The current in the wire must be ramped within about 374.25 ns from 0 to 100 A, while at these frequencies the wire acts like an inductor of L$\approx$ 800 nH.

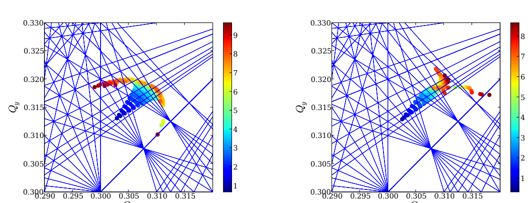

Figure 5: Tune footprints (0-8σ) without (left) and with wire compensation (right). The color encodes the starting amplitude.

Using a low-impedance cabling which is matched on the generator side, and unmatched on the load side, and letting the inductivity define the slope of the current ramp seems to be the only promising low-power option. Figure 6 (b) displays the simulated emittance growth as a function of the Gaussian rms cire-current noise. The dependence is quadratic as expected. Allowing an emittance growth of

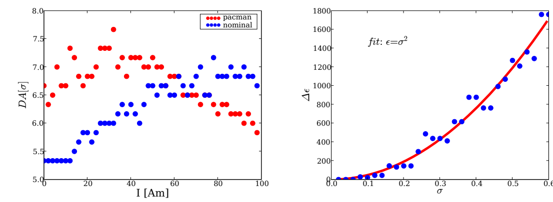

Figure 6: Top left: DA as a function of wire current for a nominal and the extreme PACMAN bunch; at intermediate wire currents the DA is increased for both bunches. Top right: emittance growth due to white Gaussian noise on the wire current.

10% in 20 h, we obtain a maximum allowed noise level of $\sigma_{noise} = 3.1$ mA, which for a linear ramp is equivalent to a timing precision of less than 0.02 ns. We have identified two possible approaches that might loosen the requirements: Simulations confirmed that a transverse feedback could damp oscillations prior to filamentation. At highest beam currents such feedback might also be needed to cure unrelated impedance-induced beam instabilities. Alternatively, one can conceive a feedback system for the generator itself [6]: The filamentation time t_f in LHC is about 100 turns. Any error that is corrected in much less than t_f does not increase the beam emittance. Therefore it is possible to measure the error of the applied wire current and compensate for this error 3 turns later (the LHC fractional tunes are 0.32 and 0.31, close to the third integer). This second current supply will need to switch only low currents and should therefore perform better and be easier to develop. Simulations confirm that the correction after three turns is highly effective, and that, therefore, a 10 times smaller absolute error for the lower-current corrector supply allows relaxing the precision requirements for the main wire current supply by the same factor.

Upgrades

In the following we will compare three upgrade scenarios: (1) the nominal optics for higher charge (NHC), i.e., with a bunch population of 1.5×10^{11} protons, about 30% above the nominal value, (2) the "low β max" optics (LB) [2], and (3) a "compact" optics (CP) [2]. In the latter two cases the wire will need to be positioned at different locations, in order to retain equal β functions in both planes, as is summarized in Table 1. The larger β functions at the wire, as compared to the nominal optics, allow for a thicker wire and possibly active cooling. The average phase advance between the LR encounters and the wire is almost identical in all three optics. Due to the larger number of

LRBB encounters and the higher bunch charge, the wire current will need to be increased. Simulated footprints with and without wire compensation are compared in Figs. 7, 8, and 9.

Table 1: Parameters of the three optics.

variable	NOM	LB	CP
$\beta*$ [m]	0.55	0.25	0.25
particles/bunch [10^{11}]	1.5	1.15	1.15
#LRBBIs	15	17	21
wire position [m]	104	136	170
β_{wire} [m]	1780	3299	2272

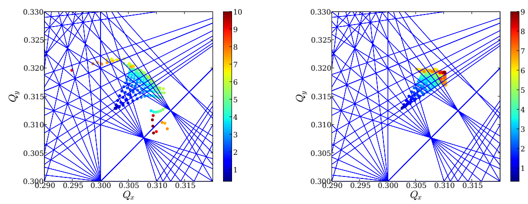

Figure 7: Uncompensated (left) and compensated tune footprints (right) for the nominal optics with increased beam current. The compensation increases the DA from 4.33 to 6.33σ.

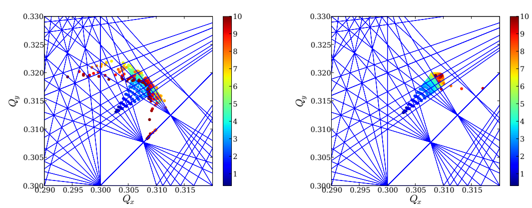

Figure 8: Uncompensated (left) and compensated tune footprints (right) for the low β-max optics. The compensation increases the DA from 5.166 to 7.1σ.

ELECTRON LENS

An electron lens could not only be used as a bunch-by-bunch tune corrector, but could eliminate the remaining tune spread due to the Head-on collision (HOC). Although the HOC itself does not cause beam-loss it is a feeding mechanism transferring particles from the center of the bunch to the borders, where other nonlinearities (LRBBI, multipole errors) then extract them. Once again noise is a crucial issue. Noise is introduced by a fluctuating electron current as well as by small variations in the lens-beam alignment. Figure 10 illustrates the lens-beam positioning stability required for the low β-max optics. With the electron lenses placed at the same locations as the wires before, a turn-by-turn beam-lens alignment stability of better than 0.355 μm is necessary in order to keep the emittance growth at a tolerable level. As the electron lens compensates for a large part of the beam-beam tune spread, it increases the filamentation time, thereby "auto-mitigating"

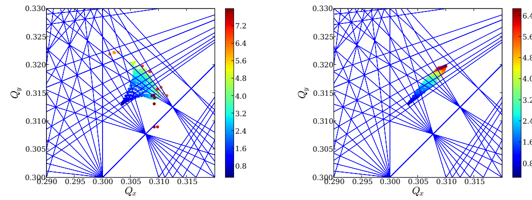

Figure 9: Uncompensated (left) and compensated tune footprints (right) for the compact optics. The compensation increases the DA from 4 to 5.2σ.

the effect of its own noise. The right picture in Fig. 10 illustrates the dramatic shrinkage of the tune footprint due to the combination of wire compensation and electron lens.

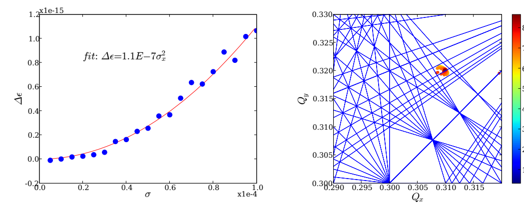

Figure 10: Left: emittance growth due to an electron lens with a random position offset. Right: tune footprint for combined wire and electron-lens compensation.

CONCLUSION

We demonstrated the effectiveness of the wire compensation in many possible scenarios, and commented on the possible usefulness of additional electron lenses for head-on compensation. Experimental studies with wire compensators are currently carried out at RHIC [7] and at the CERN SPS [8].

ACKNOWLEDGMENTS

We thank F. Caspers and T. Kroyer for discussions on possible technical implementation of the pulsing-unit and J.-P. Koutchouk for continuous feedback. We gratefully acknowledge the help of R. de Maria.

REFERENCES

[1] F. Zimmermann, TUZAKI02, these proceedings.

[2] O. Brüning, R. De Maria, R. Ostojic, CERN LHC-PROJECT-Report-1008 (2007).

[3] J.-P. Koutchouk, PAC'01 Chicago, p. 1681 (2001)

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

[5] U. Dorda et al, EPAC'06, Edinburgh, p. 2158 (2006).

[6] J.-P. Koutchouk, private communication (2007).

[7] W. Fischer et al, TUPAS095, these proceedings.

[8] F. Zimmermann et al, PAC'05 Knoxville, p. 686 (2005).

