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EXPLOITING THE BEAM-BEAM WIRE DEMONSTRATORS IN THE NEXT LHC RUN 3*

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Abstract

After the successful experiments performed during the LHC Run 2 with the Beam-Beam Wire demonstrators installed, on Beam 2, in the frame of the HL-LHC project, two of the four wire demonstrators were moved to Beam 1. The objective is to gain operational experience with the wire compensation also on that beam and therefore fully exploit the demonstrator's potential. This paper proposes a numerical validation of the wire implementation using Run 3 scenarios and explores the optimization of those devices in that respect.

INTRODUCTION

In the Large Hadron Collider (LHC) [1] and its future upgrade, the High-Luminosity LHC (HL-LHC) [2, 3], numerous Beam-Beam Long-Range (BBLR) interactions occur around the Interaction Points (IP) where the two beams come closer to each other and share the same vacuum chamber. Those interactions have a detrimental effect on the beam lifetime, especially with reduced crossing angles or increased beam intensities [4]. Higher intensity beams will gradually be delivered in the next LHC Run 3, with the recent completion of the LHC Injector Upgrade (LIU) [5]. In order to prove the mitigation of the BBLR effect, four demonstrators of wire compensators have been installed in the LHC, on Beam 2 only, following the work described in [6–8]. The objective was to demonstrate the feasibility of such a compensation during the LHC Run 2. The corresponding experimental and numerical results have been discussed in [9–11].

Following those positive results, two of the four wire collimators have been moved from Beam 2 to Beam 1 in order to fully exploit the potential of those demonstrators, using the BBLR compensation during the physics production of the LHC Run 3 operation. This paper describes the implementation of the wires in this perspective, and gives an overview of their beneficial effect in terms of Dynamic Aperture (DA) [12].

IMPLEMENTATION OF THE WIRE COMPENSATORS IN RUN 3

The wire compensators demonstrators are embedded in some of the machine tertiary collimators [13], which constrains the transverse beam-wire distance. Each collimator jaw hosts one wire, and the two wires of each collimator are connected in series so that the even multipole strengths (quadrupole, octupole, ...) are doubled while the other multipoles cancel out. This "2-jaws powering" configuration is used in order to maintain a reasonable octupolar efficiency of the wires even if the physical transverse distance from the beam is increased during the nominal operation of the machine. During the LHC Run 3, the wires are planned to be powered at the end of each fill, after the foreseen β-leveling (β^* of 30 cm). In this configuration, the wire collimators are planned to be opened at 8.5 σ_{coll}[1] [14].

The linear tune shifts induced by the wires can reach a 10^{-2} level and must be compensated. In order to avoid an important β-beating, the tune compensation is done locally using the nearby quadrupoles. During the LHC Run 2 this feed-forward system was using the Q4 and Q5 quadrupoles. During the LHC Run 3, given the larger tele-indexes range [15], this solution is not adequate and a new feed-forward system is therefore proposed, using the two Q4 quadrupoles, located on each side of the IP. Since the phase advance between the two is about π, the β-beating induced by the correction is limited and confined to the region between the two Q4s. A summary of the implementation of this new feed-forward system, in terms of tune and chromatic effects, is presented in Fig. 1, for Beam 1. Both tunes and chromaticities are within acceptable limits, for our purposes. The same sanity checks have been carried out for Beam 2, showing similar results.

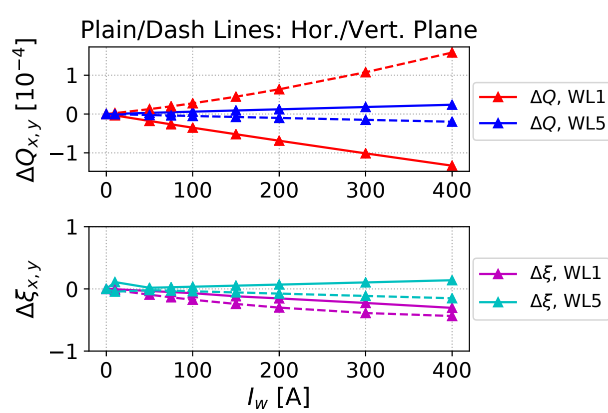

Figure 1: Tune feed-forward for the wire compensators during the LHC Run 3 (Beam 1). The notation "WLX" corresponds to "Wire Left", followed by the IP number.

The following sections report tracking simulation results[2] using SixTrack [16], and for a beam energy of 7 TeV.

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[1] The definition of σ_{coll} assumes a normalized emittance of 3.5 µm.
[2] In the presented numerical studies, only Beam 1 is tracked.

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WIRE CURRENT EFFECT ON THE DA

During the nominal operation of the LHC, the transverse beam-wire distance is set by the collimator openings, as defined by machine protection considerations. The physical beam-wire distances are reported in Table 1 for the two considered collimator openings.

Table 1: Transverse Distances Between the Wires Center and the Beam Center, as a Function of the Collimators Opening ($\beta^* = 30$ cm)

Coll. Open.	Wire L1 (Vert.)	Wire L5 (Hor.)
7.5 σ_{coll}	8.39 mm	11.15 mm
8.5 σ_{coll}	9.1 mm	12.23 mm

The wire currents are left as the only adjustable parameters. One can study the impact of these currents on the DA. The following simulations reproduce an end-of-fill configuration, after the β-leveling ($\beta^* = 30$ cm, corresponding to a crossing angle of 158 μrad). The bunch population is set to $1.1 \cdot 10^{11}$ protons per bunch, and the nominal octupole current is set to +350 A. Figure 2 shows the dependency of the average DA on the wire currents, in the heretofore described configuration.

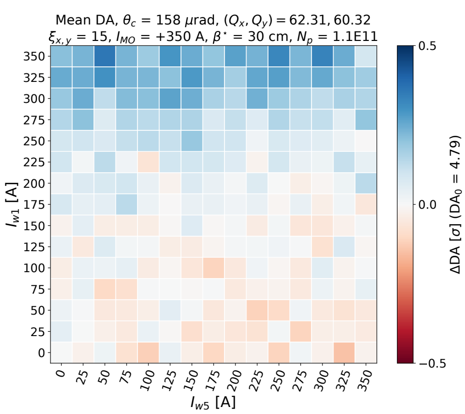

Figure 2: Average DA variation as a function of the wires current.

An improvement of about 0.4σ average DA is observed, in particular in the case of the wires in IR1 since the wires in IR5 are further away from the beam (see Table 1). For I_{w1} set to 350 A and I_{w5} set to 300 A or 50 A the DA improvement is maximized.

TUNE SCANS

The reference tunes of the machine are set to $Q_x = 62.31$ and $Q_y = 60.32$, but it has been shown that the DA can be improved by moving the tunes away from this nominal working point [17]. One can study the impact of the wire compensators on the available tune space, that is the area in the (Q_x, Q_y) space, where the DA is greater than 5σ. Figure 3 shows the DA variation between a configuration with the wires on ($I_{w1} = 350$ A and $I_{w5} = 300$ A) and a configuration without them, as a function of the horizontal and vertical tunes.

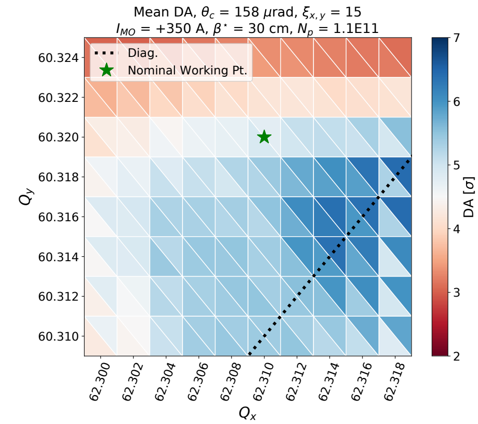

Figure 3: Average DA variation as a function of the horizontal and vertical tunes. The lower left triangle is the DA without the wires, the upper right triangle with the wires.

The wires improve the DA mostly in between the nominal working point and the diagonal. This creates a more comfortable region to accommodate additional non-linear effects such as a bunch-by-bunch parameters spread due to beam-beam interactions or electron cloud effects.

BBLR MITIGATION USING THE LANDAU OCTUPOLES

The octupoles powered at +350 A, ensure sufficient tune spread so that the beams remain stable, even when separated (no HO collision). However, it has been shown experimentally that with the ATS optics and high tele-indexes, strong negative octupoles can also mitigate the BBLR interactions effects, while ensuring the beam stability [18]. Figure 4 shows the average DA dependency on the wire currents (assumed to be equal in IR1 and IR5) and the octupole currents.

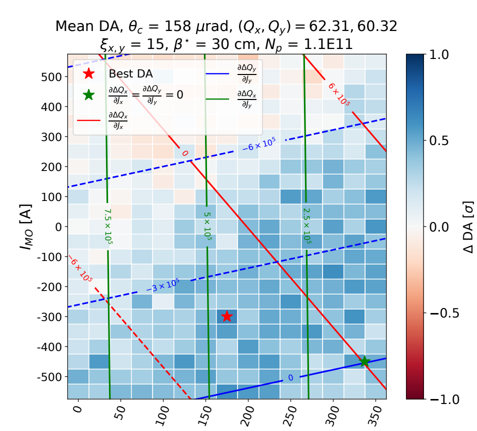

Figure 4: Average DA variation as a function of the octupoles and wires currents. The colored lines corresponds to the iso-detuning, taking into account the BBLR interactions, the wire compensators and the Landau octupoles.

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Taking into consideration the contributions of the BBLR interactions, the octupoles and the wires, it is possible to overlap the DA scan with the iso-detuning lines corresponding to the direct and cross terms of the linear detuning with amplitude [19, 20].

A negative polarity of the octupoles current can contribute to the mitigation of the BBLR interactions. The configuration where both the direct terms of the linear detuning vanish improves the DA by about 0.5σ. Moreover, better DA gains can be attained. For instance, a gain of 0.7σ is observed for the wires powered with 175 A and the octupoles current set to -300 A. Finally, the DA seems correlated to the compensation of the vertical detuning.

BUNCH INTENSITY AND CROSSING ANGLE

At the end of the β-leveling, the crossing angle is set to 158 µrad and Fig. 5a shows the DA dependency on the crossing angle and the bunch intensity, without the use of the wire compensators. For a bunch population of $1.1{\cdot}10^{11}$ protons per bunch, a crossing angle of 158 µrad is the limit for which the DA remains above 5σ. However, the luminosity leveling goal of $2{\cdot}10^{34}$ Hz$\cdot$cm^{-2} stands far from this limit (the iso-luminosity line is computed assuming 2808 collisions in IP1 and IP5). The wires could improve the machine performance reach by allowing smaller crossing angles for the same bunch intensity.

Figure 5b shows the same DA study, with the wires in IR1 and IR5 powered at 350 and 300 A respectively and the octupoles set at +350 A, as in the nominal configuration. One can observe that the wires could allow for a reduction of crossing angle of about 5 to 10 µrad after the β-leveling. As expected, the luminosity gain would be marginal. However, the main objective of the systematic powering of the compensator is to gain experience in operating such devices during the physics production.

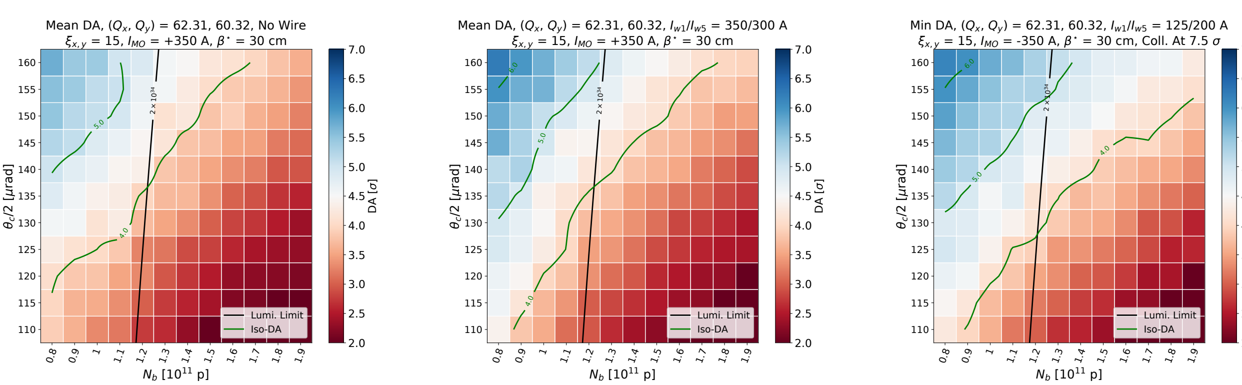
Considering a smaller gap in the wire collimators (from 8.5 to 7.5 σ_{coll}, see Table 1) [14], and by a global optimization of the wire currents and the octupole settings, the best DA configuration (absolute gain of about 1σ) can be found by powering the wires in IR1 with 125 A and the wires in IR5 with 200 A. Figure 5c then shows the DA dependency on the bunch population and the crossing angle, using this configuration. In that case, and for a bunch population of $1.1{\cdot}10^{11}$, it is possible to further reduce the crossing angle from 158 µrad down to 145 µrad, keeping the DA around 5σ. In operation, one could then consider operating a crossing angle anti-leveling, keeping the instantaneous luminosity constant for an additional couple of hours. This could lead to an increase of the integrated luminosity by about 2% over the year.

CONCLUSION

Four BBLR demonstrators are currently installed in the LHC, on Beam 2. Thanks to the positive results obtained during the LHC Run 2, two of those demonstrators are being moved from Beam 2 to Beam 1 and are planned to be powered systematically at the end of each fill during the next LHC Run 3. Tracking simulations have shown that even with the current technical constraints - in particular, in terms of beam-wire transverse distances - a beneficial effect from the compensators can be expected. A marginal gain of DA has been observed, together with an improvement in the available tune space, allowing to accommodate additional non-linear detuning effects. However, a gain in integrated luminosity of about 2% could be obtained, by reducing the beam-wire distance and by inverting the octupoles polarity.

Despite the expected marginal performance gain during the LHC Run 3, the main aim of using the wire demonstrators in nominal operational conditions is to gain operational experience and further explore its potential as a complement to the HL-LHC baseline scenario.

The authors would like to thank the entire LHC wire compensation team, the LHC Operation team and all the people involved in the wires experiment, as well as the HL-LHC project management for their constant support.



(a) No wires. (b) Nominal Configuration. (c) Best Configuration.

Figure 5: Average DA as a function of the bunch population and the crossing angle. The luminosity is computed assuming 2736 colliding bunches, an energy of 7 TeV, normalized emittances of 3.5 µm and a bunch length of 7.5 cm.

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