ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP053

NUMERICAL OPTIMIZATION OF DC WIRE COMPENSATION IN HL-LHC *

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Abstract

The electromagnetic field generated from a set of DC wires parallel to the beam opens the path to the compensation of the beam-beam long-range (BBLR) interactions for the future operation of large hadron colliders, in particular for the upcoming High Luminosity upgrade of the Large Hadron Collider (HL-LHC). The effectiveness and simplicity of a current carrying wire are critical for overcoming some technical constraints of the machine. In order to better understand the potential of this device for the HL-LHC, various simulation studies are presented. The different observables are the dynamic aperture and the frequency analysis.

INTRODUCTION

The two proton beams of the Large Hadron Collider (LHC) and its High Luminosity upgrade (HL-LHC) [1,2] share the same beam pipe at the insertion regions, where the experiments are located. At these locations, the particles in a given beam interact with the electromagnetic field generated from the counter rotating beam, at both sides of the interaction points (IP). The detrimental effect from these beam-beam long range (BBLR) interactions in particular for the particles away from the beam center was extensively studied in [3–6]. A technically simple solution for the compensation of the BBLR interactions is the use of current currying wires [7,8]. The beneficial impact of such compensation device in HL-LHC optics version 1.3 at the end of the luminosity leveling is presented in this work. Successful experimental studies accompanied by numerical optimizations specifically for the LHC are presented in [9,10].

The benefit of BBLR compensation can be evidenced from the dynamic aperture (DA) plots of Fig. 1. The DA calculations found in this paper are numerically performed using SIXTRACK [11], with the baseline configuration of the HL-LHC (see Table 1) without considering any magnet imperfections, but with high octupoles and chromaticity [12]. The BBLR interactions are assumed to be generated by two dimensional Gaussian charge distributions [13] and 25 BBLR kicks per IP per side are used. The HO collisions at IP2 and IP8 are not simulated. Also the BBLR kicks at IP2 and IP8 are not simulated since they are quite weaker than the ones in IP1 and IP5. The tune for the baseline scenario of the HL-LHC is numerically optimized to give the best minimum DA [14]. In Fig. 1, the red curve represents the case with only head on (HO) collision at IP1 and IP5, whereas the blue curve represents the case with HO collisions and BBLR kicks. The minimum normalized triplet aperture of the HL-LHC is indicated with the black dashed line, and roughly corresponds to the DA when BBLR collisions are not present. The impact of the BBLR effect is reflected by the blue curve, for which the minimum DA is slightly above 6 σ.

Table 1: HL-LHC Baseline Configuration at the End of the Luminosity Leveling

Parameters	**Symbol**	**Value [units]**
Energy	E	7000 [GeV]
Bunch population	N_p	1.2×10^{11}
Normalized emittance	ε_n	2.5 [µm]
Horizontal tune	Q_x	62.315
Vertical tune	Q_y	60.32
Horizontal chromaticity	ξ_x	+15
Vertical chromaticity	ξ_y	+15
Beta function at IP1 & IP5	$\beta^\star$	15 [cm]
Crossing angle at IP1 & IP5	Φ_{15}	500 [µrad]
Landau octupole current	I_o	-300 [A]

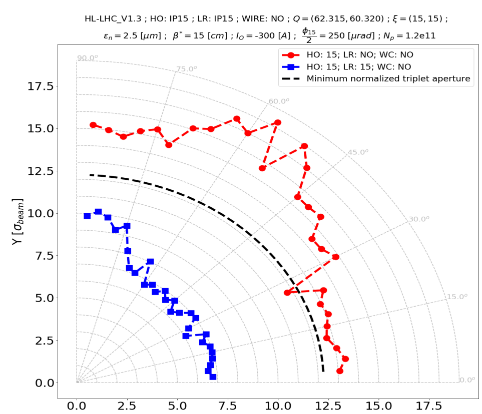

Figure 1: Dynamic aperture for the case with only head-on collision at IP1/5 (red line) and for the case with head on and BBLR kicks (blue line). The minimum normalized triplet aperture is shown in black.

NUMERICAL OPTIMIZATION

For the HL-LHC optics it is shown in [8] that all leading order resonance driving terms (RDTs) driven by the BBLR kicks are minimized if the wire compensators are placed at a longitudinal position where the beta ratio $\left(\frac{\beta_{x,w}}{\beta_{y,w}}\right)$ is close to 0.5 or 2. Such a longitudinal position is used in the simulation and is at 195 m left and right from both IPs. At this spe-

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ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP053

cial longitudinal position, the wires transverse distance ($\mathcal{D}$) and their current (I_{wire}) for anti-symmetric optics between the left (L) and the right (R) sides of the IPs $\frac{\beta_{x,wR}}{\beta_{y,wR}} = \frac{\beta_{y,wL}}{\beta_{x,wL}}$ and negligible phase advance between the BBLR kicks are $\mathcal{D} = 7.36$ mm$= 8.85\ \sigma_{\text{wireR1}}$ and $I_{\text{wire}} = 122$ A-m. However, these distances for this configuration are quite close to the beam and certainly closer to the position of the TCTs for HL-LHC, which are located at around 10 σ. Thus, the transverse position of the wire must be larger than 10 σ from the perturbed beam, in order to comply with the planed machine protection considerations and in particular with the machine elements and collimation aperture hierarchy. Numerical simulations are performed, using as a parameter the wire transverse distance and its current and the results are presented in this section.

In order to constraint further the large parameter space, the DA scans are performed by using combinations of wire currents and distances that are able to cancel particular resonances. The natural choice is the first non compensated RDTs, which are the octupolar (4,0)-(0,4) ones. The characteristic tune spread generated from the BBLR kicks and the corrected one using the wires with the aforementioned theoretical configuration are shown in Fig. 2. For these footprint studies the head on kicks are not applied and the current of the arc octupoles is zero. The red footprint refers to the HL-LHC without BBLR interactions and wire compensator. The small tune spread shown is a second order effect generated by the lattice sextupoles. By adding the BBLR kicks, a strong tune spread appears (blue footprint). With the use of the wires (green footprint) the tune spread from the BBLR interactions is well compensated and it is comparable to the red one.

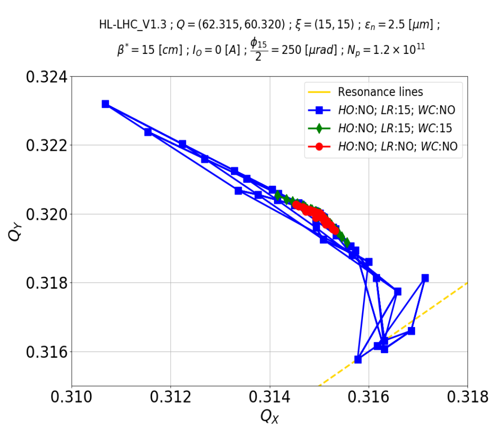
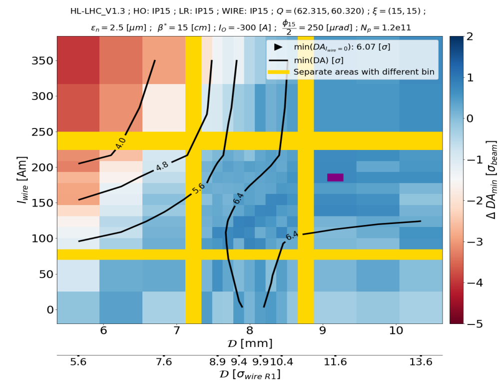
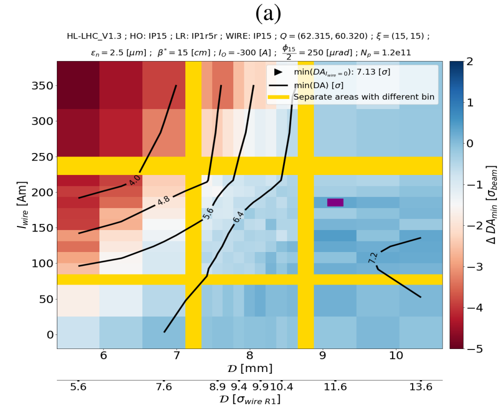


Figure 2: Tune footprint plots for three different configurations: 1) chromaticity (red), 2) chromaticity + BBLR kicks (blue), 3) chromaticity + BBLR kicks + wire compensation (green).

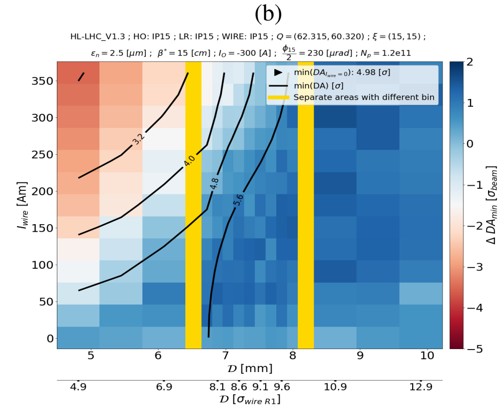
Using -300 A at the arc octupoles (which already induce a partial reduction of the BBLR tune-spread) and various wire configurations, the difference of their minimum DA from that without wire (ΔDA_{min}) is shown in Fig. 3a (represented by the color-coding). There are wire configurations ($\mathcal{D}$,I_{wire})



(a)



(b)



(c)

Figure 3: Minimum DA difference for different wire configurations from the case without wire: (a) baseline scenario, (b) baseline scenario with the half BBLR interactions and (c) pushed scenario.

at large transverse distances ($\mathcal{D} > 10\sigma$) with ΔDA_{min} close to 1σ (deep blue color). The positive ΔDA_{min} means that the minimum DA is improved up to 1 σ on top of the baseline minimum DA with the use of wire compensators. The configuration indicated with purple rectangle is among the best. The effect of the different wire configurations on the PACMAN bunches is also studied. Using only the right BBLR kicks of the IP1 and IP5 and the same wire configurations as before, the minimum DA difference (ΔDA_{min}) from the case without wire is plotted in Fig. 3b. There are

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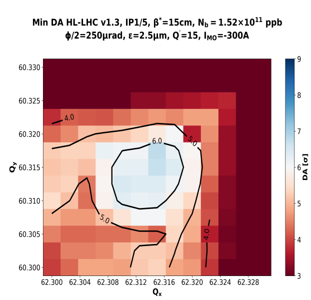
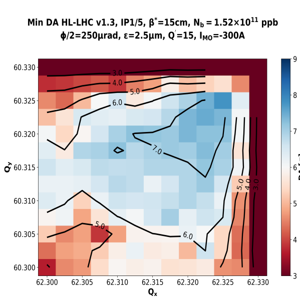
some configurations with positive $\Delta DA_{\min}$ and one of them is the same one as in the case of the bunches with all the BBLR kicks, marked with a purple rectangle. Overall, the good wire configurations do not degrade the lifetime of the PACMAN bunches. Fig. 3 demonstrates that there are different wire configuration with large distances and higher wire integrated currents that can lead to DA increase even for the nominal scenario, at the end of levelling, without degrading the lifetime of the PACMAN bunches. As the resulting DA is 7σ, this provides margin to either push further the crossing angle and thereby increase the protected triplet aperture (i.e. reduce irradiation and/or enable a $\beta^\star$ reduction). Such a pushed scenario with crossing angle reduced at 460 μrad can be fully operational with the use of wires as it is shown in Fig. 3c. The minimum target DA for an efficient operation of the collider (good lifetime) is at 6σ [15]. For this pushed scenario the minimum DA without wire is around 5σ and with good wires configurations can be larger than the 6 σ limit. In fact, there are good wire configurations with large transverse distances that provide minimum DA up to 6.5 σ, leaving some extra margin for reducing further the crossing angle.

The wire effectiveness is also illustrated in Fig. 4 where the ultimate scenario ($N_p = 1.52 \times 10^{11}$) of the HL-LHC is used. In Fig. 4a the correlation of the working point (WP) as a function of the minimum DA for the ultimate scenario of the HL-LHC is shown. As can be seen there are not good WP (minimum DA larger than 6 σ) away from the diagonal. Adding the wire compensators ($\mathcal{D}$ = 8 mm and I_{wire} = 154 A-m for this study) Fig. 4b, the WP area with DA above 6 σ (blue) is increased and many good operational tunes away from the diagonal can be found. Similar enlargement of the WP area can be achieved with all the good wire configurations. In fact, wire compensation enables the choice of a fixed working point through the levelling process guaranteeing good lifetime.



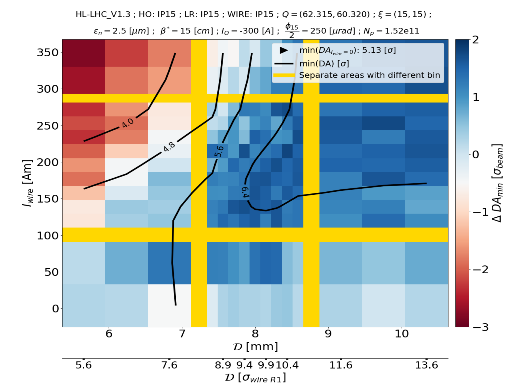
(a)



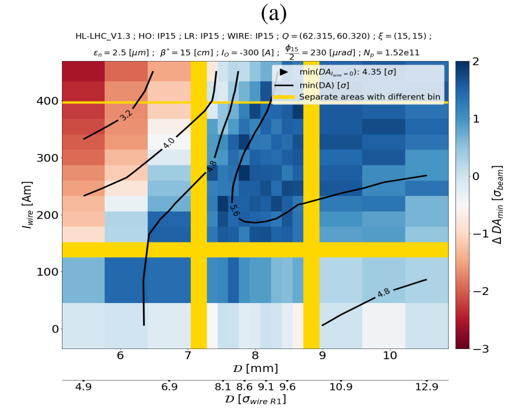
(b)

Figure 4: The minimum DA for different working points: (a) the ultimate scenario of HL-LHC and (b) the ultimate scenario of HL-LHC with wire compensators.

The good wire set ups at the ultimate and the pushed ultimate scenarios can be seen in Fig. 5a and Fig. 5b respectively. The minimum DA without wire is less than 6 σ for both cases. With the use of wires the minimum DA can be increased up to 6.9σ at the ultimate scenario and up to 6.1 σ for the pushed ultimate one (i.e. with reduced crossing angle). Good wire configurations at large transverse distances ($\mathcal{D} > 10\sigma$) are obtained. The already beneficial impact of the wire can be further improved with the use of new optimized WP leaving margin for further reduction of the $\beta^\star$ and/or the crossing angle.



(a)



(b)

Figure 5: Minimum DA difference for different wire configurations from the case without wire: (a) ultimate scenario and (b) pushed ultimate scenario.

CONCLUSION

In this paper, the benefits from using DC wires for the BBLR compensation in the HL-LHC nominal round optics are showcased. A 1σ improvement at the baseline scenario, 1.5σ at the pushed, 1.8σ at the ultimate and 1.8σ at the pushed ultimate scenarios are observed. Additionally, it is shown that with good wire configurations the DA of the PACMAN bunches is not affected and that the area of good working tunes is increased. In order to obtain a broader understanding of the wire performances, additional numerical and analytical studies are on-going. Also, an operational scenario with wires is being worked out in order to quantify clearly their positive impact to machine performance. Finally, based on the DC wires effectiveness (for the BBLR compensation) they might be considered for future upgrades of the HL-LHC baseline.

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