ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL103

# POTENTIAL AND CONSTRAINTS OF A BEAM-BEAM WIRE COMPENSATOR IN THE HL-LHC ERA

G. Sterbini, A. Bertarelli, Y. Papaphilippou, A. Poyet, A. Rossi, CERN, Geneva, Switzerland
P. Bélanger, TRIUMF, Vancouver, Canada



*Abstract*

The compensation of the long-range beam-beam interactions by DC wires is currently being investigated as an option for enhancing machine performance during the High-Luminosity LHC era. In this paper, we report and comment on the potential of wire compensation during the first HL-LHC run. The results are based on numerical simulations and optimizations of the machine dynamic aperture varying the wire position and current, taking into account the latest optics and beam scenarios and the constraints imposed by the corresponding settings of the HL-LHC collimation system.

## INTRODUCTION

In circular colliders, the electromagnetic interaction between the two counter-rotating beams can have a detrimental effect on the beam lifetime and, therefore, on the collider's luminosity performance. In particular, the effect on the beam lifetime of the so called long-range beam-beam interactions (LRBB) were predicted [1–3] and observed [4, 5] in the LHC. Differently from the head-on beam-beam interactions (HOBB), the LRBB can be approximated with Laplacian potentials and can be compensated with the use of an adequate set of magnetic multipoles. To produce such a set of multipoles, the installation of DC wires in the LHC was proposed in [6], followed by a rich experimental campaign in the CERN SPS [7]. Their potential for HL-LHC [8] was investigated in [9], where the wire compensation was optimized by minimizing the resonances excited by LRBB interactions. It was shown that, thanks to the antisymmetry of the optics and the phasing between the LRBB of the same Interaction Region (IR), it is possible to compensate locally all relevant resonance driving terms with a reduced number of wires (two wires per beam and IR) placed at a specific $\beta_x/\beta_y$ ratio. Unfortunately, this approach requires a wire-beam distance that is not compatible with the present constraints of the LHC and HL-LHC collimation system, where all elements of the machine need to be protected by the collimation hardware, implying that they should be in the shadow of the aperture of the tertiary collimators [10]. An experimental campaign performed in 2017-18 [11, 12] showed that it is possible to observe a compensation effect with the wires in the shadow of the tertiary collimators at the expense of a larger wire current. In fact, the possibility to use the wires in HL-LHC within machine protection constraints was studied via numerical optimization in [13], where the performance gain was shown, mainly focusing on the end-of-levelling ($\beta^*$ = 15 cm) and on the ultimate luminosity scenarios. In this paper we will explore the potential of wire compensation in the early stages of the HL-LHC era (i.e. from the start of the run in 2029).

## CONFIGURATION OF THE WIRES

Presently, the beam-beam compensation wires (BBCWs) are not part of the HL-LHC baseline scenario. Nevertheless, for each of the high-luminosity interaction regions (IR around Interaction Point 1 and 5, IP1 and IP5), two slots on the beam line are reserved for a possible BBCW installation . The reserved slots are positioned between the Q4 and Q5 matching quadrupoles (Fig. 1), where the two beams are travelling in separated vacuum chambers.

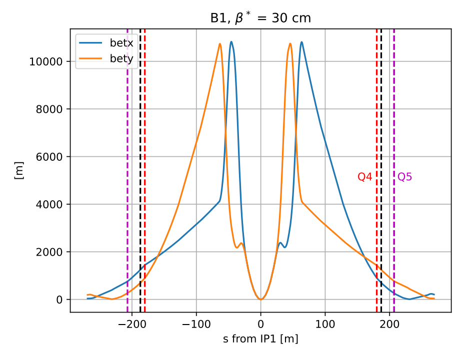


Figure 1: BBCW slots between the Q4 and Q5 matching quadrupoles in IR1 (similar configuration in IR5). The optics functions of Beam 1 for $\beta^*$ =30 cm are also shown.

In the simulations, we assumed four BBCW assemblies as depicted in Fig. 2. Each assembly has 3×1 m-long modules per beam. Each module is able to carry up to 150 A, totalling an integrated wire current of 450 A m per assembly [14].

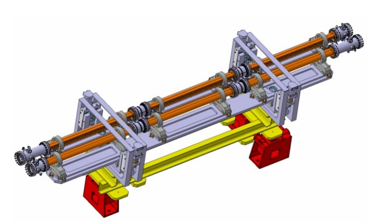

Figure 2: Wire compensator assembly (courtesy of A. Bertarelli). In the simulations we assume four such assemblies in the machine, one per side in IR1 and IR5.

We considered the HL-LHC optics version 1.5 without the MS10 sextupoles [15] and a $\beta^*$ =30 cm (round optics scenario for the first year of the commissioning of HL-LHC run) with chromaticity, Q′, of 15 in both planes. The beam intensity, $N_b$, is 1.8 × $10^{11}$ ppb with a normalized emittance,

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL103

Table 1: Positions and optics functions of Beam 1 at the wire modules for a $\beta^*$=30 cm. To be noted that, while the wire module effective length is 1 m, its mechanical one is 1.25 m.

| | s from IP [m] | $\beta_x$ [m] | $\beta_y$ [m] |
|---|---|---|---|
| module 3, left | -189.50 | 1176.12 | 632.12 |
| module 2, left | -188.25 | 1209.93 | 664.12 |
| module 1, left | -187.00 | 1244.31 | 696.86 |
| module 1, right | 187.00 | 698.20 | 1243.97 |
| module 2, right | 188.25 | 664.72 | 1210.73 |
| module 3, right | 189.50 | 632.10 | 1177.87 |

$\epsilon_n$, of 2.5 $\mu$m in both planes. The half crossing angle, $\frac{\phi_{\mathrm{IP1,5}}}{2}$, between the two beams at IP1,5 is assumed equal to 225 $\mu$rad, if not stated differently. The crossing plane is horizontal in IP1 and vertical in IP5. Concerning the beam-beam configuration, the beams are colliding in all IPs (IP8 is levelled by separation at $\mathcal{L}$= 2 × $10^{33}$ cm$^{-2}$s$^{-1}$ and the beams are separated by 5 $\sigma$ in IP2). The Landau octupole current, $\mathrm{I_{MO}}$ is 100 A, if not stated differently.

Multi-parametric, weak-strong, numerical simulations were performed following the approach presented in [16]. The figure of merit of the machine configuration is the Dynamic Aperture, DA, namely the region in phase space where the particle motion is stable [17]. The settings of the machine are considered viable for DA≥ 6 $\sigma$. We use the Xsuite libraries [18] for the particle tracking. The BBCWs are assumed as thin elements [19] and the optical functions at their positions are reported in Table 1. They are lying in the crossing plane of the nearby IP and are positioned between the two beams. From Table 1, one can see that the beam $\sigma$ at the BBCWs ranges from 0.46 to 0.65 mm. When referring to the wire-beam distance in $\sigma$, we are considering the largest $\sigma$ value among all BBCWs (e.g. positioning the wires at 16 $\sigma$ from the beam implies, assuming $\max_{\mathrm{BBCWs}}\sigma$ = 0.65 mm, that all wires are at 10.4 mm from the beam).

As mentioned, the BBCWs should be in the shadow of the tertiary collimator (TCT) aperture. Assuming the TCT settings reported in [15] (13.2 $\sigma$ for $\beta^*$=20 cm, that correspond to 11.4 $\sigma$ for $\beta^*$=15 cm), two scenarios are envisaged.

- **Scenario A**: if the TCT-beam physical distance remains constant during the $\beta^*$-levelling (constant distance in mm), then the BBCWs have to be at a transverse distance larger than 16.1 $\sigma$ for $\beta^*$=30 cm.
- **Scenario B**: if the TCT-beam normalized distance remains constant during the $\beta^*$-levelling (fixed distance in $\sigma$), then BBCWs have to be at a transverse distance larger than 11.4 $\sigma$ for $\beta^*$=30 cm.

In the simulations, we neglect the dipolar effect of the BBCWs assuming that the standard orbit feedback will correct for it. On the other hand, the quadrupolar effect of the BBCWs is compensated in the simulations by a local tune correction using the Q4 quadrupoles.

# RESULTS

In Fig. 3, the reference DA is represented, colour coded, as a function of the horizontal and vertical tunes, $Q_x$ and $Q_y$ respectively, and without using the BBCWs. The green boxes indicate the tune settings with a DA≥ 6 $\sigma$ that are in the $Q_y > Q_x + 5 \times 10^{-3}$ region. The latter condition is related to the LHC injection tunes and the coupling resonance constraints. Although there are working points allowing for a sufficient DA, the margin and the available tune space to accommodate bunch-by-bunch tune variation (e.g., due to electron cloud [20]) is limited.

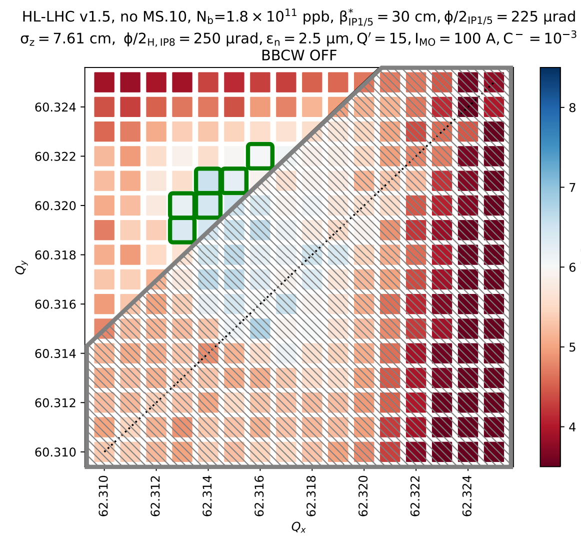


Figure 3: DA tune scan with BBCWs OFF with $\beta^*$ = 0.30 m, $N_b$ =1.8 × $10^{11}$ ppb, $\phi_c/2$ = 225 $\mu$rad at IP1/5.

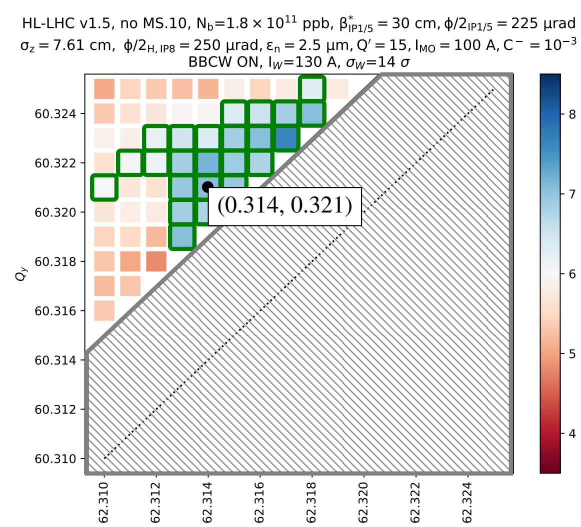


Figure 4: DA tune scan with BBCWs ON, $I_w$ =130 A at 14 $\sigma$, with $\beta^*$ = 0.30 m, $N_b$ =1.8 × $10^{11}$ ppb, $\phi_c/2$ = 225 $\mu$rad at IP1/5.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL103



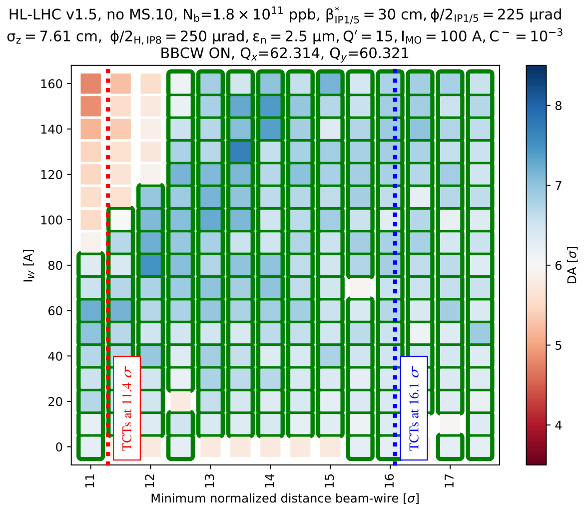


Figure 5: DA scan varying wire-beam distance and wire current with $\phi/2$ =225 $\mu$rad in IP1/5.

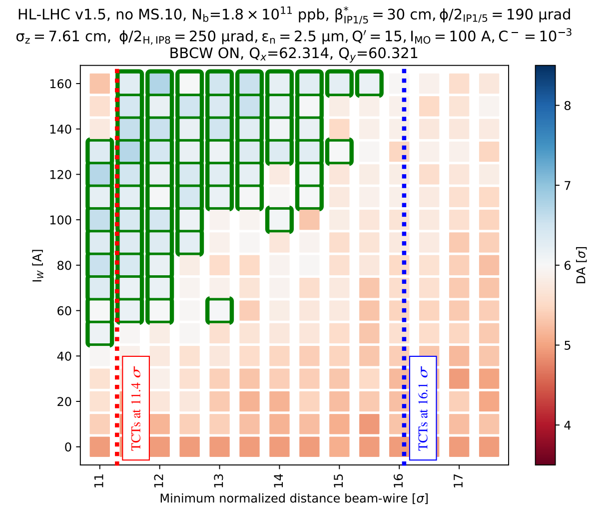


Figure 6: DA scan varying wire-beam distance and wire current with $\phi/2$ =190 $\mu$rad in IP1/5.

We explored the potential of the BBCWs in this configuration by recomputing the tune scan after placing the BBCWs at 14 $\sigma$ from the beam with a current of $I_W$ =130 A, as shown in Fig. 4. Due to the compensation effects of the wires, the DA is significantly increased (up to 2 $\sigma$ gain) and, consequently, the available tune space is enlarged.

From this plot, we can select an optimal working point, e.g., (0.314, 0.321), to perform a scan in the other two important dimensions of the parameters space, namely the beam-wire distance and the wire current as shown in Fig. 5. The green boxes refer to conditions matching the minimum DA requirements. The plot shows that there is a significant flexibility on the selection of parameters. In this scenario the BBCWs are compatible with Scenarios A (TCTs at 16.1 $\sigma$ for $\beta^*$=30 cm) and B (TCTs at 11.4 $\sigma$ for $\beta^*$=30 cm) and with the condition $I_W \leq$150 A.

The additional DA margin introduced by the BBCWs can be exploited for an overall optimization of the machine performance, e.g., by reducing the beam crossing angle, hence limiting the voltage requirements on the HL-LHC crab cavities. In Fig. 6 we recompute the parameter scan of Fig. 5, but reducing the half-crossing angle from 225 to 190 $\mu$rad. In this configuration the BBCWs are compatible with Scenario B but not with Scenario A. Following the approach presented in [21, 22], we explored the use of the arc octupoles in combination with the BBCWs. The results are shown in Fig. 7, where only a modest contribution from the arc octupoles is observed with $I_{MO}$ = −50 A assuming the BBCWs at 16 $\sigma$. The plot also shows that, for this configuration, the DA gain provided by octupoles alone ($I_W$ =0 A) is not sufficient to reach the DA target of 6 $\sigma$.

## SUMMARY

In this paper we presented the potential of DC wire compensation in the early part of the HL-LHC era, when the crab cavities are still undergoing commissioning. The BBCWs

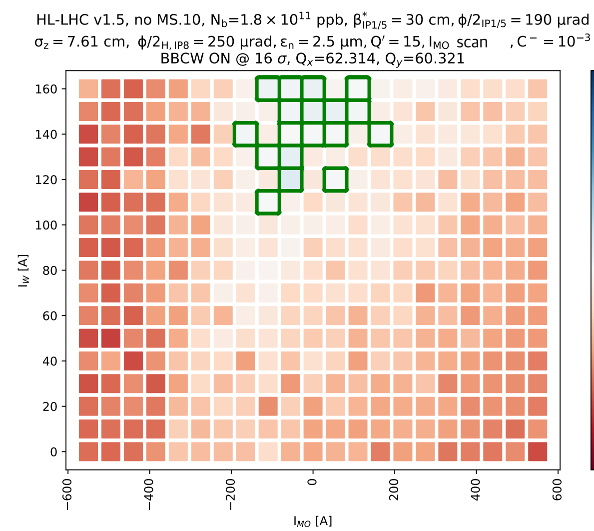


Figure 7: DA optimization using BBCWs at 16 $\sigma$ and the arc octupoles ($\phi/2$ =190 $\mu$rad in IP1/5).

allow the crossing angle to be reduced from 225 to 190 $\mu$rad in a configuration compatible with the tertiary collimation at 11.4 $\sigma$ at $\beta^*$=30 cm, with the possibility to retract the wires from the tertiary limit by ≈2 $\sigma$. The BBCWs could also be combined with arc octupole correction. These studies in fact show that the target DA value can even be achieved by positioning the wires at 16 $\sigma$ using a current of $I_W$ <150 A with an arc octupole current of −50 A. The added flexibility provided by BBCW compensation can be exploited to improve the overall machine performance of the HL-LHC in a beam-beam dominated regime.

The authors would like to acknowledge S. Kostoglou and G. Iadarola for their help with Xsuite code, H. Bartosik, S. Fartoukh, D. Kaltchev, S. Redaelli and R. Tomás for their input and encouragement and the HL-LHC management for the support.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPL103

# REFERENCES


[1] W. Herr, "Beam-beam effects in the LHC," *Part. Accel.*, vol. 50, no. CERN-SL-94-92-AP. LHC-NOTE-301. CERN-LHC-Note-301, 69–81. 14 p, 1994. https://cds.cern.ch/record/272882

[2] Y. Papaphilippou and F. Zimmermann, "Weak-strong beam-beam simulations for the Large Hadron Collider," *Phys. Rev. ST Accel. Beams*, vol. 2, p. 104 001, 1999. doi:10.1103/PhysRevSTAB.2.104001

[3] Y. Papaphilippou and F. Zimmermann, "Estimates of Diffusion due to Long-range Beam-beam Collisions," *Phys. Rev. Spec. Top. Accel. Beams*, vol. 5, no. LHC-Project-Report-600. CERN-LHC-Project-Report-600. 7, 074001. 22 p, 2002. doi:10.1103/PhysRevSTAB.5.074001

[4] W. Herr and G. Papotti, *ICFA mini-workshop on beam-beam effects in hadron colliders*, en, 2014. doi:10.5170/CERN-2014-004

[5] T. Pieloni *et al.*, "Beam-beam effects long-range and head-on," in *Proceedings of 6th Evian Workshop on LHC beam operation*, 2016, 111–122. 12 p. https://cds.cern.ch/record/2294524

[6] J.-P. Koutchouk, "Principle of a correction of the long-range beam-beam effect in LHC using electromagnetic lenses," CERN, Tech. Rep. LHC-PROJECT-NOTE-223, 2000. https://cds.cern.ch/record/692058

[7] F. Zimmermann, "10 Years of wire excitation experiments in the CERN SPS," in *Proceedings of ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders*, 2014, 153–166. 14 p. doi:10.5170/CERN-2014-004.153

[8] G. Apollinari *et al.*, *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1*. CERN, 2017. doi:10.23731/CYRM-2017-004

[9] S. Fartoukh *et al.*, "Compensation of the long-range beam-beam interactions as a path towards new configurations for the High Luminosity LHC," *Phys. Rev. Spec. Top. Accel. Beams*, vol. 18, no. CERN-ACC-2015-0095, 121001. 23 p, 2015. doi:10.1103/PhysRevSTAB.18.121001

[10] G. Valentino *et al.*, "Final implementation, commissioning, and performance of embedded collimator beam position monitors in the Large Hadron Collider," *Phys. Rev. Accel. Beams*, vol. 20, no. 8, p. 081 002, 2017. doi:10.1103/PhysRevAccelBeams.20.081002

[11] G. Sterbini *et al.*, "First results of the compensation of the beam-beam effect with DC wires in the LHC," in *10th International Particle Accelerator Conference*, 2019, WEYYPLM3. doi:10.18429/JACoW-IPAC2019-WEYYPLM3

[12] A. Poyet *et al.*, *First experimental evidence of a beam-beam long-range compensation using wires in the Large Hadron Collider*, 2022. https://arxiv.org/abs/2203.08066

[13] K. Skoufaris *et al.*, "Numerical optimization of dc wire parameters for mitigation of the long range beam-beam interactions in High Luminosity Large Hadron Collider," *Phys. Rev. Accel. Beams*, vol. 24, no. 7, p. 074 001, 2021. doi:10.1103/PhysRevAccelBeams.24.074001

[14] L. Sito *et al.*, "Beam-Beam Long Range Compensator Mechanical Demonstrator," in *these proceedings*, 2023.

[15] R. Tomás *et al.*, "Operational scenario of first high luminosity LHC run," *JACoW*, vol. IPAC2022, pp. 1846–1849, 2022. doi:10.1088/1742-6596/2420/1/012003

[16] D. Pellegrini, S. Fartoukh, N. Karastathis, and Y. Papaphilippou, "Multiparametric response of the HL-LHC Dynamic Aperture in presence of beam-beam effects," in *8th International Particle Accelerator Conference*, 2017. doi:10.1088/1742-6596/874/1/012007

[17] M. Giovannozzi, "Proposed scaling law for intensity evolution in hadron storage rings based on dynamic aperture variation with time," *Phys. Rev. ST Accel. Beams*, vol. 15, p. 024 001, 2 2012. doi:10.1103/PhysRevSTAB.15.024001

[18] *Xsuite*, https://xsuite.readthedocs.io.

[19] A. Patapenka, Y. Papaphilippou, R. De Maria, and A. Valishev, "Simulations in Support of Wire Beam-Beam Compensation Experiment at the LHC," TUPOB17, 2017. doi:10.18429/JACoW-NAPAC2016-TUPOB17

[20] G. Iadarola, L. Mether, N. Mounet, and L. Sabato, "Linearized method for the study of transverse instabilities driven by electron clouds," *Phys. Rev. Accel. Beams*, vol. 23, p. 081 002, 8 2020. doi:10.1103/PhysRevAccelBeams.23.081002

[21] T. Pieloni, J. Barranco García, X. Buffat, and C. Tambasco, "Study of Beam-Beam Long Range Compensation with Octupoles," in *8th International Particle Accelerator Conference*, 2017. doi:10.18429/JACoW-IPAC2017-TUPVA027

[22] S. Fartoukh, M. Solfaroli, J. C. De Portugal, A. Mereghetti, A. Poyet, and J. Wenninger, "Achromatic telescopic squeezing scheme and by-products: From concept to validation," *Phys. Rev. Accel. Beams*, vol. 24, no. 2, p. 021 002, 2021. doi:10.1103/PhysRevAccelBeams.24.021002