ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEYYPLM3

FIRST RESULTS OF THE COMPENSATION OF THE BEAM-BEAM EFFECT WITH DC WIRES IN THE LHC *

G. Sterbini†, D. Amorim, H. Bartosik, A. Bertarelli, R. Bruce, X. Buffat, F. Carra, L. Carver, G. Cattenoz, E. Effinger, S. Fartoukh, N. Fuster, M. Gasior, M. Gonzalez, A. Gorzawski, G. Hemelsoet, M. Hostettler, G. Iadarola, R. Jones, N. Karastathis, S. Kostoglou, I. Lamas, T. Levens, L. Medina, D. Mirarchi, J. Olexa, S. Papadopoulou, Y. Papaphilippou, D. Pellegrini, M. Pojer, A. Poyet, L. Ponce, S. Redaelli, A. Rossi, B. Salvachua, H. Schmickler, F. Schmidt, K. Skoufaris, M. Solfaroli, R. Tomas, G. Trad, D. Valuch, C. Xu, C. Zamantzas, P. Zisopoulos, CERN, Geneva, Switzerland
A. Levichev, BINP, Novosibirsk, Russia
M. Fitterer, A. Valishev, FERMILAB, Batavia IL, USA
D. Kaltchev, TRIUMF, Vancouver, Canada

Abstract

The compensation of the long-range beam-beam interactions using DC wires is presently under study as an option for enhancing the machine performance in the framework of the High-Luminosity LHC Project (HL-LHC). The original idea dates back more than 15 years ago. After the installation of four wire prototypes in the LHC in 2018, a successful experimental campaign was performed. The experimental setup and the main results are reported in this paper.

INTRODUCTION

One of the main limiting factors of the performance of circular hadron colliders is related to the electromagnetic interaction between the two beams [1]. In the Large Hadron Collider (LHC), they occur both during the collisions at the interaction point (IP), head-on beam-beam effect (HO), and in its proximity, long-range beam-beam effect (LR). The impact of the beam-beam effect was evaluated during the LHC design phase [2–5], observed during its initial operation [6] and taken into account for the performance optimization during the recent LHC run [7, 8].

Due to the specific betatronic phasing of the LRs for a given interaction region (IR), it was proposed to compensate their non-linear kicks by using the magnetic field of two DC wires positioned on each side of the IP [9]. This triggered several numerical studies and analytical efforts [10–17]. In complement to the theoretical investigations, the effect of the wire on the beam was experimentally tested in SPS [18], RHIC [19] and implemented in operation in DAΦNE [20]. In addition, a rich experimental program was conducted in TEVATRON to study the LR compensation effect with electron lens devices [21]. Despite the positive and encouraging results of these experiments, they could not be conclusive for the beam-beam configuration of the LHC and HL-LHC.

Given all these premises, in the framework of the HL-LHC studies [22, 23], four prototypes of wire compensators were designed, embedded in the jaws of tertiary collimators and installed in LHC during 2017 and 2018 [24]. The hardware design choices and the experimental program goals were

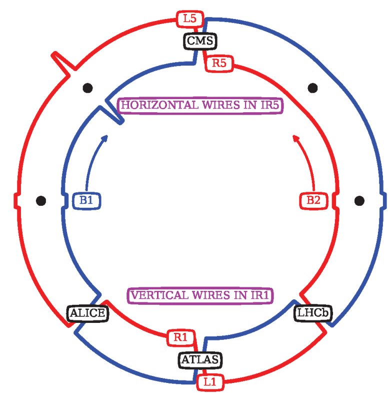

Figure 1: The location of the four wire prototypes in LHC during 2018. Not to scale.

discussed in [25, 26]. In the following sections we summarize and comment the hardware setup and the main outcomes of this experimental campaign. The numerical simulations for the LHC wire experiments and the study of possible wire configurations for HL-LHC (round optics) are described in [27, 28], respectively.

EXPERIMENTAL SETUP

During 2018, four wire prototypes were available for experimental studies in the LHC. They were installed on Beam 2 (B2, Figure 1) in the left and right side of the high luminosity IPs, IP1 (ATLAS) and IP5 (CMS). For convenience they are labelled L1, R1, L5 and R5, referring to the corresponding IP side (right, R, or left, L) and IP number, 1 or 5. For round ATS optics, the crossing angle between the two beams lies in the vertical (horizontal) plane in IP1 (IP5). The wires were positioned in the same plane as the crossing. This configuration prevented to test the wire in flat ATS optics where, due to the present aperture constraints, the crossing plane is horizontal (vertical) in IP1 (IP5). The prototypes consist of copper wires embedded in the jaws of tertiary collimators [24]. Each of the two jaws of the collimator houses a wire. Depending of the cabling configuration one or both wires can be powered. Each wire can carry up to 350 A

* Research supported by the HL-LHC project.
† guido.sterbini@cern.ch

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEYYPLM3

across their round cross-section diameter of 2.48 mm. Their effective length is ≈ 1 m. The cooling of the wire (≈ 1 kW of dissipated power at 350 A) is guaranteed by the cooling circuit of the collimator jaw. The four wires can be powered with four independent power converters. To compensate the dipolar and quadrupolar effect of the wire, an orbit and tune feed-forward were implemented, using the orbit corrector and the two quadrupoles closer to the wire in order to minimize spurious orbit and beta-beating leakage. During the experiments, in addition to the orbit feed-forward, the LHC orbit feedback was enabled (whereas the LHC tune feedback was not). The choice of the longitudinal positions of the wires (Table 1) was driven by the technical constraints of their integration in the collider: the special wire-equipped collimators (with the exception of L1) replaced existing collimators slots. A The jaws of the collimator are motorized

Table 1: Wire prototypes' longitudinal positioning. The β values refer to the ATS round optics at $\beta^* = 30$ cm [29]. For completeness, the layout names of the collimators housing the wires are added.

Wire prototype	**s from IP [m]**	$\frac{\beta_x[\mathrm{m}]}{\beta_y[\mathrm{m}]}$
L1, TLCVW.A5L1	-176.17	430/1271=0.34
R1, TCTPV.4R1	145.94	1826/1279=1.43
L5, TCL.4L5	-150.03	1127/1768=0.64
R5, TCTPH.4R5	147.94	1798/1204=1.49

and, thanks to pick-up devices directly placed on them [30], a precise horizontal and vertical alignment of the wire with respect to B2 is possible. In all the compensation experiments, the wires were powered only at top energy (6.5 TeV) and when the beams were colliding. The constraints of the prototypes and of the LHC collimation hierarchy [31] set a minimal transverse B2-wire distance. The experimental program was therefore split into two stages, the Low Intensity (LI) and the High Intensity (HI) experiment. In the LI experiment, the compensation principle with low intensity in B2 (2 nominal bunches in B2 and 3 trains in B1) was validated by reducing the beam-wire distance settings in the four collimators housing the wires (5.5 collimation sigmas [31], σ_{coll}, half-gaps). In the HI experiment, the compensation potential was explored with high intensity in B2 (3 nominal LHC trains both in B1 and B2) but increased beam-wire distance. The tertiary collimators housing the wires R1 and R5 have to be set at 8.5 σ_{coll} half-gaps, whereas the operational position limits on the L1 and L5 jaw positions prevent, without additional setup time, to use them in the HI experiment. In order to partially recover the LI compensation potential, the even-multipoles contributions (quadrupole, octupole,…) of R1 and R5 were doubled by re-configuring them as shown in Figure 2 (quadrupolar configuration). In Table 2 we summarize the beam-wire centre distances in the wire plane for the two configurations.

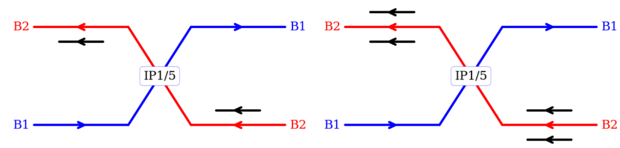

Figure 2: A schematic representation to compare the dipolar configuration (*left*, adopted for the LI experiment) and the quadrupolar configuration (*right*, adopted for the HI experiment). Not to scale.

Table 2: B2-wire Distance in the Wire Plane and Wires' Current

Wire prototype	**LI experiment**	**HI experiment**
L1	-7.41 mm, 350 A	not used
R1	7.42 mm, 320 A	9.83 mm, 350 A
L5	-7.15 mm, 190 A	not used
R5	8.24 mm, 340 A	11.10 mm, 350 A

EXPERIMENTAL RESULTS

The metric adopted to quantify the compensation effect of the wires is based (*i*) on the beam losses (therefore the beam lifetime) and (*ii*) on the effective cross-section [32] of the bunches, σ_{eff}, defined as

$$\sigma_{\mathrm{eff}} = -\frac{1}{\sum_{IP} L_{IP}}\frac{dN}{dt} \tag{1}$$

where L_{IP} is the instantaneous luminosity of a given IP and N is the number of proton for a given bunch. In an ideal situation, σ_{eff} corresponds approximately to the pp inelastic cross section (e.g., ≈ 80 mb at 6.5 TeV). The measurement procedure followed in the experiment was to setup the machine in a LR-dominated regime and, by switching regularly on and off the wire compensation, observe the behaviour of the beam losses and σ_{eff}.

Low Intensity Experiment

In Figure 3, the σ_{eff} evolution of the two bunches of B2 is shown during the LI experiment. The first bunch is colliding HO in IP1 and IP5 (PACMAN bunch) whereas the second bunch is experiencing, in addition to the HOs, LRs (regular bunch). The objective of the ideal compensation is to improve the lifetime of the regular bunch without degrading the one of the PACMAN. The experiments starts with both bunches at the reference $\sigma_{\mathrm{eff}} \approx 80$ mb. At 08h20 the transverse emittances of the bunches underwent a controlled blow-up for populating the bunch halo and, after that, the behaviour of the two bunches differentiates showing the LRs effect on the regular bunch. By gradually switching on the compensation, the σ_{eff} of the second bunch recovered (orange) almost completely the initial σ_{eff} and no degradation was observed on the PACMAN bunch (blue). At 09h15 the half-crossing angle ($\theta_c/2$) was reduced from 150 to 140 μrad while keeping the beam-wire separation constant. Even in this condition, the wire compensation was

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEYYPLM3

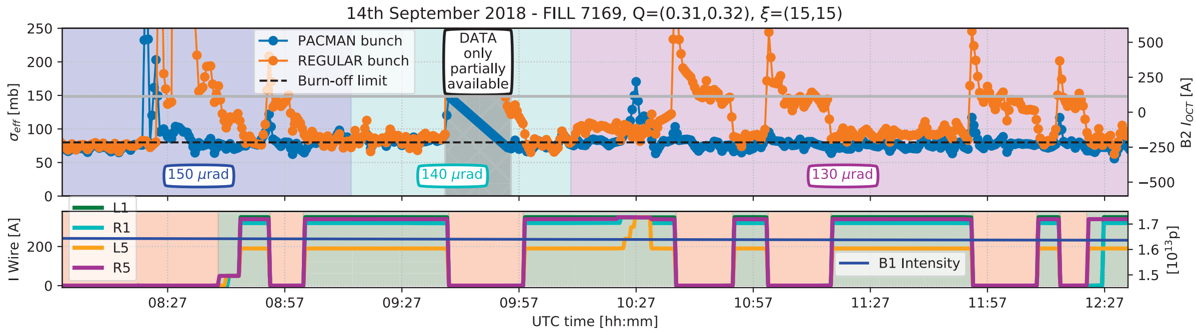

Figure 3: Results of the Low Intensity experiment.

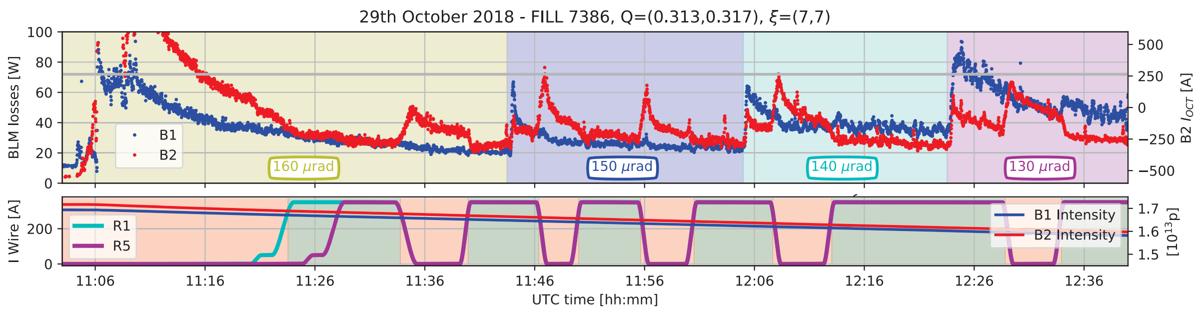

Figure 4: Results of the High Intensity experiment.

effective, without showing the usual losses due to the crossing angle reduction (e.g., see B1 in Figure 4). An additional crossing angle reduction (from $\theta_c/2$=140 to 130 μrad) was performed and, in this case, a moderate degradation of the σ_{eff} of the regular bunch was visible. Starting from 10h25, a partial scan confirmed that the proposed wire currents are optimal within the tested sets. In the rest of the experiment the compensation was cycled on and off. The beneficial effects of the wires was systematically observed. At 12h20, the compensation using only the IR5 wires was tested, confirming that, in this particular experimental setup, the IR5 wires are more effective than the IR1 ones.

High Intensity Experiment

In Figure 4, the evolution of Beam Loss Monitor (BLM) losses for both beams are shown in the HI configuration, that is in the compensation compatible with the LHC operational cycle. Tunes, chromaticity and arc octupole current during the experiment were set at their operational values (Figure 4). After having put the trains in collision at $\theta_c/2$ = 160 μrad (11h06) and after a luminosity optimization (11h10), the B2 losses (red) were larger than the B1 ones (blue). At 11h20 the compensation was switched on and a significant reduction of the B2 losses was measured. The reproducibility of this observation was confirmed by switching off and on the wires. By reducing the $\theta_c/2$ to 150 μrad the losses increased but the ones of B2 were limited by the compensation. By switching off the compensation (11h46), the B2 losses increased significantly and they could be minimized by powering back the wires. Similar compensation scans were performed by further reducing the $\theta_c/2$ (from 150 to to 140 μrad, at 12h05, and from 140 to to 130 μrad, at 12h24). In all the tested configurations, the beneficial effect of the wire compensation was systematic and reproducible and a 20-30% reduction of the B2 losses was observed.

CONCLUSIONS

We presented the main results of the experimental campaign of the LHC wire compensation performed during the last months. For the first time, the effectiveness of the long-range beam-beam compensation using DC wires was demonstrated in an operating hadron machine. The wire prototypes were tested in a variety of configurations showing, in all of them, their positive impact on the lifetime of the regular bunches without over-compensating the PACMAN bunches. After a convenient re-cabling of the prototypes, the compensation was also tested in the LHC operational configuration, where a reduction of 20-30% of the Beam 2 losses could be achieved. Following these encouraging results, it was proposed (i) to use the wires routinely during the next LHC operation period in the High-Intensity configuration and (ii) to equip also the Beam 1 with wires by moving two wire prototypes (L1 and L5) from Beam 2 to Beam 1.

ACKNOWLEDGEMENTS

The authors would like to thank the HL-LHC management, the CERN Operation Team and the Machine Development Coordinators for their constant support.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEYYPLM3

REFERENCES

[1] E. Keil, "Beam-beam interactions in p-p storage rings", CERN, Switzerland, CERN-77-13, 1977.

[2] W. Herr, "Tune Shifts and Spreads due to the Long Range Beam-Beam Effects in the LHC", CERN, Switzerland, CERN-SL-90-06, 1990.

[3] "Proceeding of the Workshop on Beam-Beam Effect in Large Hadron Colliders", Geneva, Switzerland, 1999, edited by J. Poole and F. Zimmermann. https://cds.cern.ch/record/392054

[4] Y. Papaphilippou, F. Zimmermann, "Weak-strong beam-beam simulations for the Large Hadron Collider," *Phys. Rev. ST Accel. Beams*, vol. 2, p. 104001, 1999. doi:10.1103/PhysRevSTAB.2.104001

[5] Y. Papaphilippou,F. Zimmermann, "Estimates of diffusion due to long-range beam-beam collisions," *Phys. Rev. ST Accel. Beams*, vol. 5, p.074001, 2002. doi:10.1103/PhysRevSTAB.5.074001

[6] G. Papotti, X. Buffat, W. Herr, R. Giachino, T. Pieloni, "Observations of beam-beam effects at the LHC". doi:10.5170/CERN-2014-004.1, arXiv:1409.5208[physics.acc-ph]

[7] X. Buffat *et al.*, "Long-range and head-on beam-beam interactions: what are the limits?", in *Proc. 7th Evian Workshop (EVIAN'16)*, Evian, France, Dec. 2016, http://cds.cern.ch/record/2289585

[8] D. Pellegrini *et al.*, "Multiparametric Response of the LHC Dynamic Aperture in Presence of Beam-Beam Effects", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2051–2054.

[9] J.-P. Koutchouk, CERN Report, LHC Project Note 223, 2000.

[10] B. Erdelyi and T. Sen, "Compensation of beam-beam effects in the Tevatron with wires," FERMILAB, USA, Rep. FERMILAB-TM-2268-AD, 2004.

[11] T. Sen and H. J. Kim, "Simulations of Beam-wire Experiments at RHIC", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper THPAN114, pp. 3492–3494.

[12] U. Dorda, "Compensation of long-range beam-beam interaction at the CERN LHC", CERN, Switzerland, CERN-THESIS-2008-055, 2008.

[13] H. J. Kim and T. Sen, "Simulations of Long-Range Beam-Beam Compensation in LHC", in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper WE6PFP031, pp. 2558–2560.

[14] J. Qiang, "3D Strong-Strong Simulations of Wire Compensation of Long-Range Beam-Beam Effects at LHC", in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper WE6PFP037, pp. 2576–2578.

[15] T. Rijoff, "Testing long range beam-beam compensation for the LHC luminosity upgrade", CERN, Switzerland, CERN-THESIS-2012-377, 2012.

[16] A. S. Patapenka *et al.*, "Simulations in Support of Wire Beam-Beam Compensation Experiment at the LHC", in *Proc. NA-PAC'16*, Chicago, IL, USA, Oct. 2016, pp. 525–527.

[17] 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. ST Accel. Beams*, vol. 18, p. 121001, 2015. doi:10.1103/PhysRevSTAB.18.121001

[18] F. Zimmermann, "10 Years of wire excitation experiments in the CERN SPS," CERN Yellow Report CERN-2014-004, pp.153-166, http://cds.cern.ch/record/1955353

[19] R. Calaga, W. Fischer, G. Robert-Demolaize and N. Milas, "Long-range beam-beam experiments in the Relativistic Heavy Ion Collider," *Phys. Rev. ST Accel. Beams*, vol. 14, p. 091001, 2011.

[20] C. Milardi, D. Alesini, M. A. Preger, P. Raimondi, M. Zobov and D. Shatilov, "Dafne Lifetime Optimization with Compensating Wires and Octupoles," arXiv:0803.1544[physics.acc-ph]

[21] V. D. Shiltsev *et al.*, "Experimental Demonstration of Beam-Beam Compensation by Tevatron Electron Lenses and Prospects for the LHC", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper TUOCKI04, pp. 728–732.

[22] Apollinari G. *et al.*, High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1, CERN, Geneva, Switzerland, 2017, http://cds.cern.ch/record/2284929

[23] L. Rossi and O. S. Brüning, "Progress with the High Luminosity LHC Programme at CERN", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper MOYPLM3, this conference.

[24] A. Rossi *et al.*, textquotedblleftProgress with Long-Range Beam-Beam Compensation Studies for High Luminosity LHC", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2358–2361.

[25] "Simulations and Measurement of Long Range Beam-Beam Effect in the LHC", 30 Nov.-1 Dec., 2015, Lyon, France, https://indico.cern.ch/event/456856/

[26] "Second workshop on Wire Experiment of Long Range Beam-Beam Effect in the LHC", 20 March, 2017, Divonne, France, https://indico.cern.ch/event/615088

[27] A. Poyet *et al.*, "Numerical Simulations of the DC Wire Prototypes in LHC for Enhancing the HL-LHC Performances", presented at the IPAC'19, Melbourne, Australia, May 2019, paper MOPMP052, this conference.

[28] K. Skoufaris *et al.*, "Numerical Optimization of DC Wire Compensation in HL-LHC", presented at the IPAC'19, Melbourne, Australia, May 2019, paper MOPMP053, this conference.

[29] The LHC optics repository, http://cern.ch/lhcoptics

[30] G. Valentino *et al.*, "Final implementation, commissioning, and performance of embedded collimator beam position monitors in the Large Hadron Collider," *Phys. Rev. ST Accel. Beams*, vol. 20, p. 081002, 2017.

[31] R. Bruce *et al.*, "Review of LHC RUN 2 machine configuration", in *Proc. 9th Evian Workshop (EVIAN'19)*, Evian, FR, Dec. 2019.

[32] F. Antoniou *et al.*, "Can we predict luminosity?", in *Proc. 7th Evian Workshop (EVIAN'16)*, Evian, France, Dec. 2016, http://cds.cern.ch/record/2289585