LHC OPTICS CORRECTIONS IN RUN 2

T. Persson, F. Carlier, J. Coello, J. Dilly, S. Fartoukh, E. Fol, A. Garcia-Tabares,
M. Giovannozzi, M. Hofer, E.H. Maclean, L. Malina, P.K. Skowronski,
M.L. Spitznagel, R. Tomás, A. Wegscheider, J. Wenninger
CERN, 1211 Geneva 23, Switzerland

Abstract

The LHC optics commissioning strategy has developed significantly since the start of Run 2. The changes have mainly been driven by the decrease of β^*, which was lowered from 80 cm in 2015 down to 25 cm in 2018. This has changed the impact of the nonlinear errors on the beam dynamics which, if left uncorrected, would have caused significant reduction in machine performance. As a consequence, the 2015 commissioning focused on the linear errors while the commissioning in 2017 and 2018 also included the correction of the nonlinear errors. This paper provides an overview of these changes and their impact on machine parameters and performance. It also reviews the optics stability and reproducibility. Furthermore, the focus on coupling has increased due to the understanding of its impact on instabilities and luminosity. The activity develop an automatic coupling-correction tool was started before the run has been completed and the software is being used in operation since 2017. The drift of the transverse coupling occurs mainly at injection and a way to mitigate such a drift is proposed for the next run.

EVOLUTION OF THE CORRECTION STRATEGY IN RUN 2

The correction strategy in 2015 was essentially the same as for Run 1, while the approach in 2018 had only few similarities. This change in correction strategy was mainly driven by the decrease of β^* as shown in Fig. 1. The different measurement and corrections that were performed each year are outlined in Tab. 1.

In general the beam commissioning was performed from left to right in the table, but due to the interplay between the different activities and the fact that some of the nonlinear corrections are calculated from the same set of measurements this does not always hold. In the following sections the corrections for the different years are described in more detail. A special focus is given to the 2018 commissioning since this has not previously been documented in detail.

2015

Following the success of the optics corrections in Run 1 [1] where the nominal optics was corrected down to β^* = 60 cm a similar commissioning strategy was employed when the machine was switched on in 2015. There were, however, some significant improvements, such as the N-BPM method, a new method to reconstruct the β-functions from the phase advances. This new method provided better precision for the reconstruction of the β-functions than the

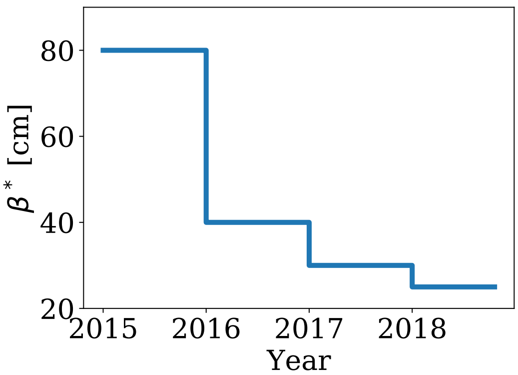


Figure 1: Minimum operational β^* as a function of time during Run 2. Note that in 2017 and 2018 the ATS optics was used.

previously used method [2]. An additional improvement was the increased AC-dipole plateau and BPM recording time, which was increased to 6600 turns from 2200 turns in 2012 [3].

The first thing that was measured in 2015 was the virgin machine without any local corrections applied. This gave the surprising result that the local errors in IR1 and IR5 were significantly different compared to 2012 [3, 4]. The reason for the difference between the two years was never fully understood. The first possible explanation is the higher running energy of 6.5 TeV compared to 4 TeV in Run 1. However, there was also a 2.51 TeV run and the local corrections needed were still compatible with those calculated for 6.5 TeV. Other potential reasons could have been different misalignment or changes in the magnetic strength [4].

An issue during the 2015 commissioning was the movement of the IR8 triplet that affected the dispersion measurements [4]. The IR8 issue came from a regulation valve that did not move correctly and a mitigation was found by changing the operating point [5]. This was not identified as a problem in the next years of commissioning.

2016

Already in 2015 it was observed that there was a systematic shift of the waist of β^* [4]. This led to the incorporation of the K-modulation results to calculate local corrections. This method was first tested in the ion commissioning in 2015 and was then fully deployed in the proton run in 2016. Using only the phase information, it is possible to find a set of corrections which all correct the phase errors. However,

Table 1: Overview of the different measurement and corrections that were performed and applied during the different years in Run 2. The (F) stands for flat orbit and the (X) stands for orbit with crossing angles. TbT is Turn-by-Turn measurement performed with the AC-dipole, virgin means that there are no corrections, Local Corrs are the corrections in the IRs, global correction refers to the correction of the β-beating using a response matrix approach, arc phase advance is to correct the global phase advance between the different arcs, a_3 is the skew sextupolar component, a_4 is the skew octupolar component, b_3 is the normal sextupolar component and b_4 is the normal octupolar component. [1], marks that the correction was active but with the same setting as the previous year, [2]Correction only for IP1, [3]Corrections based on RDTs.

Year	TbT Virgin (F)	K-mod Virgin (F)	Local Corr (F)	TbT after Local (F)	K-mod after Local (F)	IR b_4 Correction	Global Corr (F)	Arc Phase Advance	TbT + K-mod after global (F)	Chromatic Coupling Corr (F)	TbT + K-mod (X)	IR b_3 Correction	IR a_3 Correction	IR a_4 Correction	Global Corr (X)	TbT + K-mod, after Global Corr and non-linear corr (X)
2015	✓		✓	✓			✓		✓							
2016	✓	✓	✓	✓	✓		✓		✓							
2017			✓[1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓[2]	✓[2]	✓	✓
2018			✓[1]			✓[1]	✓[1]	✓[1]		✓[1]	✓	✓	✓	✓[3]	✓[1]	✓

after obtaining a precise measurement of the β-function at the IP from K-modulation, the corrections could be constrained further and a control of the β^* at the level of 1% was achieved [3, 6]. After a technical stop in June 2016, the optics was remeasured with crossing angles on as during the initial beam commissioning we had measured and corrected with flat orbit. An increase of the β-beating was observed that was consistent with feed-down from sextupolar errors in the IRs [7]. This gave additional motivation to focus on the nonlinear corrections in 2017 and to commission both linear and non-linear optics with the crossing angles on.

2017

2017 was the first year the ATS optics was used in normal operation. It was also the first time we started with local corrections already implemented. The local corrections were based on the MD results in 2016 [8]. The local corrections used in operation from the different years are shown in Tab. 2. We note that the corrections in 2016 and 2017 are identical for IR1 and IR2 and only slightly different for IR5. However, a slight degradation of the quality of the optics correction in 2017 compared with the results obtained in 2016 was observed [10–12]. The error was still in the range where it was considered acceptable and global corrections were used to improve the optics further.

2017 was also the year when focus was given to compensating the nonlinear errors in the IRs. This significantly reduced the feed-down from changes in crossing angles to coupling and tune. A dedicated correction of the β-beating with the crossing angles on was also applied to reduce the residual β-beating. The 2017 beam commissioning also profited from the new analytic N-BPM method to reconstruct the β-functions from the turn-by-turn data [9]. A detailed account of the 2017 commissioning activities is given in [10, 11].

2018 Proton

In order to save time it was decided that the 2018 commissioning would start with both local and global corrections in and, if needed, apply an additional correction. In Fig. 2 a comparison of the β-beating at $\beta^* = 30$ cm is shown. It is interesting to observe that in contrast to other years, no degradation of the linear optics quality is observed between 2017 and 2018.

The β^* was also squeezed further down to 25 cm in 2018, which is the lowest operational configuration so far in the LHC. There were no additional corrections applied between 30 cm and 25 cm. This is at least partially the reason for the increase of the RMS β-beating from 2.0% for 30 cm to 2.5% for the 25 cm optics. The β-beating for Beam 1 at 25 cm is shown in Fig. 3.

The results from the K-modulation of the β^* were less consistent, when repeated, compared to 2017, which gave rise to larger error bars. The reason could potentially be linked to tune jitter, which during certain periods is significantly larger than normal [13]. This also triggered the action to remeasure the β^* at IP1 during the first MD period [17]. The results from both 2017 and 2018 are given in Tab. 3.

Optics in the Ramp The global β-beating corrections at injection were calculated in 2016 and remained the same until the end of Run 2. The approach was to trim out the

Table 2: Local correction strengths for 2012 and all years of Run 2 for IR quadrupoles. The circuits of the final focusing quadrupoles are highlighted with a bold font. The powering of the triplets has been $|K_0|$=0.008730 m^{-2} for 2015 and 2016, but was changed slightly from 2017 onward when the ATS optics was used. In 2018 the same local corrections were used as in 2017. The polarity indicates if K_0 is positive or negative using the LHC Software Architecture (LSA) convention.

	Circuit	**Δk (10^{-5}m^{-2})**					Polarity
		2012	**2015**	**2016**	**2017**	**2018 Ion**	LSA
IR1	**ktqx1.l1**			1.23	1.23	1.23	-
	ktqx1.r1	1.0		-1.23	-1.23	-1.23	+
	ktqx2.l1	1.0	0.35	0.65	0.65	0.48	+
	ktqx2.r1	-1.4	-0.7	-1.0	-1.0	-0.83	-
	ktqx3.l1			1.22	1.22	1.22	-
	ktqx3.r1			-1.22	-1.22	-1.22	+
	kq9.l1b1	1.5					-
IR2	**ktqx1.l2**					2.23	-
	ktqx1.r2					3.41	+
	ktqx2.l2			+1.5	+1.5	1.47	+
	ktqx2.r2			-1.5	-1.5	-0.57	-
	ktqx3.l2					-2.51	-
	ktqx3.r2					1.31	+
IR5	**ktqx1.l5**		2.0	2.0	2.0	2.0	-
	ktqx1.r5		-2.0	-2.0	-2.0	-2.0	+
	ktqx2.l5	0.7	1.9	0.27	0.26	0.26	+
	ktqx2.r5	1.05	1.9	1.48	1.58	1.58	-
	ktqx3.l5			1.49	1.49	1.49	-
	ktqx3.r5			-1.49	-1.49	-1.49	+
	kq4.l5b2	3.80					-

Table 3: Measured β^* in 2017 commissioning and end of 2018 commissioning for the β^* = 30 cm optics. A list of all the measurements can be found in [17]. The K-modulation measurement was not repeated during the MD for IP5 since the results obtained during beam commissioning were more reproducible.

	IP 1 β^* [cm]				IP 5 β^* [cm]			
	Beam 1		Beam 2		Beam 1		Beam 2	
	H	V	H	V	H	V	H	V
2017	30.7 ± 0.2	30.5 ± 0.2	30.0 ± 0.3	30.0 ± 0.1	30.7 ± 0.2	30.1 ± 0.1	29.8 ± 0.1	30.4 ± 0.2
2018	30.2 ± 0.1	30.2 ± 0.8	30.7 ± 0.1	30.5 ± 0.1	30.1 ± 0.1	30.2 ± 0.1	31.2 ± 0.4	30.7 ± 0.3

injection corrections linearly throughout the energy ramp. In 2017 a measurement of the optics at 2.5 TeV showed a smaller β-beating without any corrections. This led to an revised approach where the injection corrections were trimmed out linearly from the start of the ramp to 2 TeV compared to 2017, when they were only fully trimmed out at 6 TeV. The improvement in β-beating with this approach is shown in Fig. 4.

Nonlinear corrections While no additional linear corrections were applied in 2018, significant focus was given to calculate new settings for the nonlinear correctors. The only nonlinear IR correctors which remained unchanged between 2017 and 2018 were the octupolar ones. The b_3 correctors were reiterated for both IPs and the a_3 and a_4 corrections were used for the first time in IR5 and changed slightly for IR1. A comparison of the strength of the different nonlinear correctors, together with the magnetic measurements, are given in [14]. 2018 was also the first year RDTs were used as input for setting the strength of some correctors in the LHC ring, namely the a_4. The methods to measure and correct based on the a_4 RDTs were tested in a MD in 2017 [15, 16]. Since only 3 out of the 4 a_4 correctors are operational, a compromise between correcting the two beams needed to be found. In Fig. 5 a comparison of the RDTs before and after correction in 2017 and 2018 with flat orbit is shown. In 2017, Beam 2 was improved, but the RDTs for Beam 1 were slightly increased, whereas in 2018 the corrections were successful to improve Beam 1 while leaving Beam 2 RDTs at the same level.

When the RDTs were measured with the operational crossing angle on, their amplitude changed significantly. This

Table 4: Evolution of the local coupling corrections following the LSA convention (opposite to MAD-X). [1]What was used after the commissioning (positive crossing angle in IR2), [2]After optimizing with the colinearity knob (positive crossing angle in IR2), [3]After optimizing with the colinearity knob (negative crossing angle in IR2).

	Circuit	Δk (10^{-4}m^{-2})					
		2012	**2015**	**2016-2018**	**Ion 18[1]**	**Ion 18[2]**	**Ion 18[3]**
IR1	**RQSX3.L1**	8.0	8.7	11.0	11.0	11.0	11.0
	RQSX3.R1	8.0	8.7	7.0	7.0	7.0	7.0
IR2	**RQSX3.L2**	-9.0	-16	-14.0	-8.7	-18.7	-20.7
	RQSX3.R2	-9.0	-16	-14.0	-23.2	-13.2	-11.2
IR5	**RQSX3.L5**	6.0	7.0	7.0	7.0	7.0	7.0
	RQSX3.R5	6.0	7.0	7.0	-5.0	-5.0	-5.0
IR8	**RQSX3.L8**	-7.0	-5.0	-5.0	-5.0	-5.0	-5.0
	RQSX3.R8	-7.0	-5.0	-5.0	-5.0	-5.0	-5.0

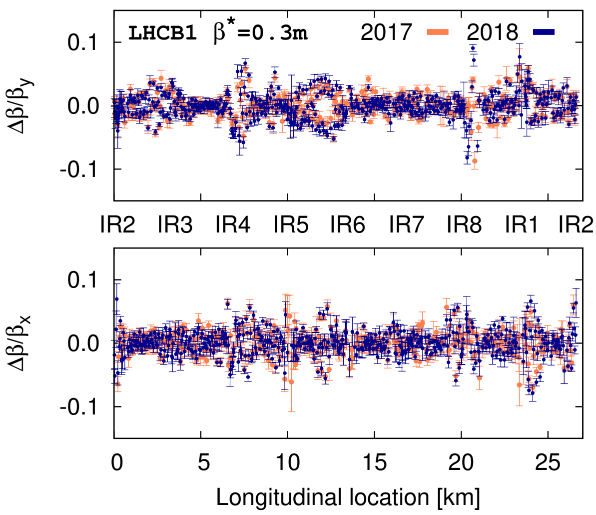


Figure 2: Comparison of the β-beating at $\beta^* = 30$ cm in 2017 and 2018 for Beam 1.

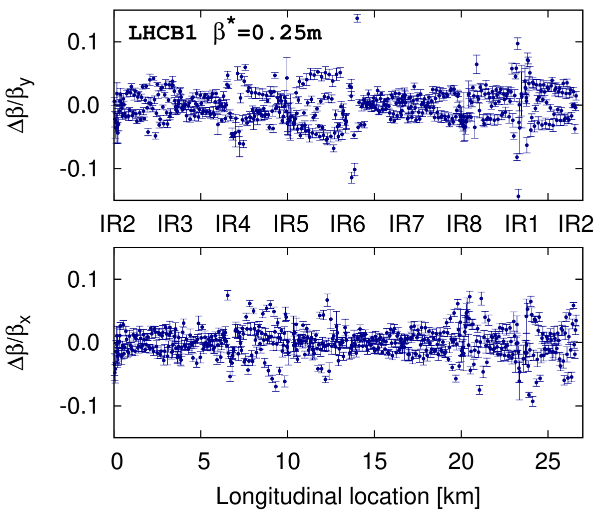


Figure 3: The β-beating at $\beta^* = 25$ cm for Beam 1.

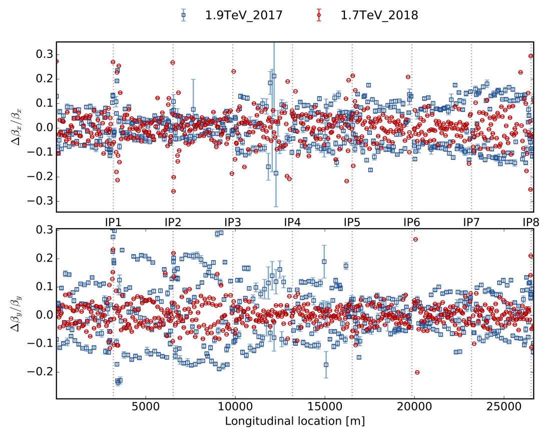
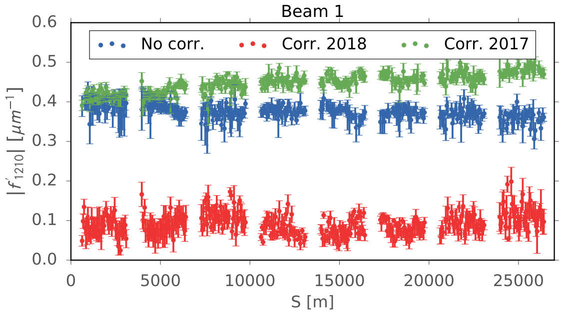
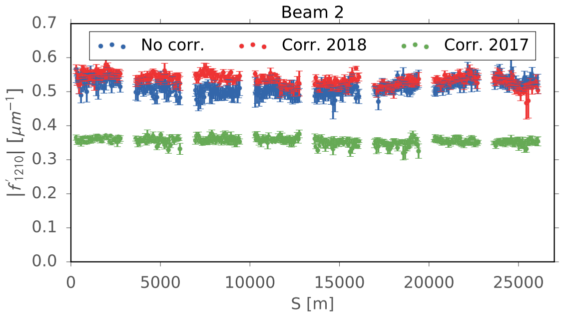


Figure 4: Comparison of the β-beating during the ramp and squeeze in 2017 and 2018. In 2017 the corrections were trimmed out fully at 6 TeV and in 2018 at 2 TeV.

indicates that there are higher order multipoles, such as decapoles or/and dodecapoles that feed-down and create the change in the a_4-RDTs. Additional evidence of the presence of higher orders was coming from amplitude detuning measurements carried out with crossing angles on. The results are shown in Fig. 6 where the red line shows the expected amplitude detuning at 30 cm, the blue the amplitude detuning with flat orbit after correction, and the grey line and measurement points show the amplitude detuning after corrections, but with the crossing angles on. We observe that the amplitude detuning introduced by the crossing angle bumps is around half of the uncorrected one. The magnetic model does include errors that are in the right magnitude to explain the observed change in amplitude detuning [17]. The asymmetry between Beam 1 and Beam 2 is such that the IR correctors cannot be used to control the amplitude detuning for both beams for the operational crossing angles and since there are no IR decapolar correctors in LHC, it would still have to be corrected with the MO [18]. In order to correct the amplitude detuning using the MO they would have to be powered for Beam 1: MOF=-108 A, MOD=142 A and for Beam 2: MOD=-70 A, for $\beta^* = 30$ cm and 6.5 TeV.



(a) Beam 1



(b) Beam 2

Figure 5: The a_4 RDTs measured for flat orbit without correction, correction tested in 2017, and 2018 correction.

2018 Ion Run

In 2018, the β^* at IR2 was squeezed down to 50 cm: a very significant step compared to 80 cm in 2015. As a consequence, the local linear coupling and phase correction needed to be recalculated. The corrections are shown in Tab.1. It was also observed that the local correction at IP1 had slightly degraded and a new one was calculated, shown in Fig. 8. The error was in the order of 10% of the uncorrected phase error, but we can observe that the situation was clearly improved.

The new local coupling corrections for IP2 were calculated using an automatic matching tool [19]. However, when the corrections were trimmed in, the settings of the right and left MQSX got swapped due to a human mistake. The phase advance between the two corrector magnets is such that the effect outside the triplet is almost invisible. Inside the triplet there are only a few BPMs and the phase advance and the strong local sources make it very hard to determine what is the optimal balance between the two correctors. The swap created about 50% reduction of the instantaneous luminosity for the ALICE experiment (IP2). This was recovered by trimming the colinearity knob [20], originally designed for flat optics, while observing the luminosity. Using this knob, which re-balances the strength of the left and right MQSX, the luminosity was recovered. In order to understand this effect in more detail simulations of the impact of strong coupling in the IRs were initiated [21]. In Fig. 7 a 2D-histogram of a Gaussian bunch consisting of 9000 particles all tracked for 10 turns in PTC is shown. In this simulation a setting of the colinearity knob of +10 was introduced to reproduce the local coupling in IP2 when the reduced luminosity was observed. There is a clear increase of the transverse beam size at IP2 compared to IP1 in both the horizontal and vertical plane. In this simulation the horizontal emittance is assumed to be 50% larger than the vertical emittance. The increase in beam size is 15% for the horizontal and 30% for the vertical plane. Using this difference in beam size it is expected that IP2 would have 67% of the luminosity of IP1. This is to be compared with the 50% that was measured with luminosity. This indicates that there are additional sources that are not yet accounted for in the simulation.

In order to avoid a similar situation in the future, several actions were taken. Firstly, an automatic method to send the calculated corrections has been created, preventing human error. However, even if the corrections would have been sent correctly, there would have been a difference to what was found optimal with luminosity. This error would have caused approximately 7% luminosity loss. In order to constrain the local coupling corrections further in Run 3, a MD was performed [22]. The idea was to introduce a rigid waist shift that breaks the symmetry between the right and left MQSX and then observing the global coupling that is significantly easier to measure than the local one. The preliminary results indicate that the method was successful but might need to be refined in order to reach the high level of accuracy needed to prevent a luminosity imbalance between the experiments. A full optimization of the optimal settings should be done by changing the colinearity knob while observing the luminosity. This strategy changes the previous strategy and needs to be studied in detail. It would also require luminosity from the experiments at an earlier stage in the beam commissioning.

It is however interesting to observe that the impact of the colinearity knob on the β^* measurement with K-modulation is small as seen in Tab 5.

CONTROL OF GLOBAL COUPLING

The development of systematic global coupling corrections had already started during Run 1. A special tool to correct the coupling based on the injection oscillations was developed [23]. Additional aspects of coupling were also studied, such as chromatic coupling, which was then later used in operation in 2017-2018 [24]. In Run 2, additional focus was given to linear coupling due to its link to transverse instabilities [25]. A new method, based on using the ADT as an AC-dipole to excite coherently a single bunch, was tested and developed during MDs [26]. Furthermore, in 2017 a big effort was made to put in place an operational tool to measure and correct the linear coupling. This was achieved through a fruitful collaboration between ABP, CO, OP and RF [27, 28]. The improved control of the coupling has enabled to lower the powering of the Landau octupoles without increasing the impact of instabilities [29]. It has been used for thousands of measurements throughout the cycle. The

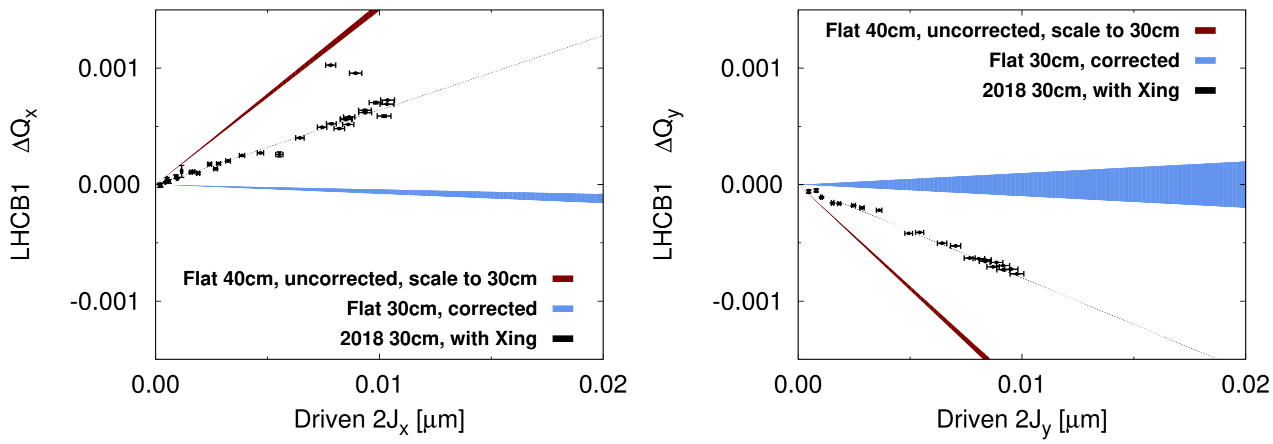


Figure 6: Amplitude detuning at β^*=30 cm, without any correction (flat orbit), with correction (flat orbit), and with correction (crossing angles on).

Table 5: Measured β^* from beam commissioning and the MD for different crossing angles and colinearity knobs settings. The colinearity knob is defined as MQXS.3L2 = $10^{-4}\mathrm{m}^{-2}$ and MQXS.3R2= $-10^{-4}\mathrm{m}^{-2}$. There are no measurements of Beam 1 during the MD since the beam was lost already during the ramp.

IP 2					
		Beam 1 β^* [cm]		Beam 2 β^* [cm]	
Colinearity Setting	Crossing angle [μ rad]	H	V	H	V
0	137	51.6 ± 0.1	50.5 ± 0.4	51.0 ± 0.1	50.3 ± 0.9
0	-137	52.3 ± 0.1	51.3 ± 0.3	50.5 ± 0.2	49.8 ± 0.9
-12	-137			51.4 ± 0.2	50.3 ± 0.1
-5	-137			50.8 ± 0.2	50.6 ± 0.1

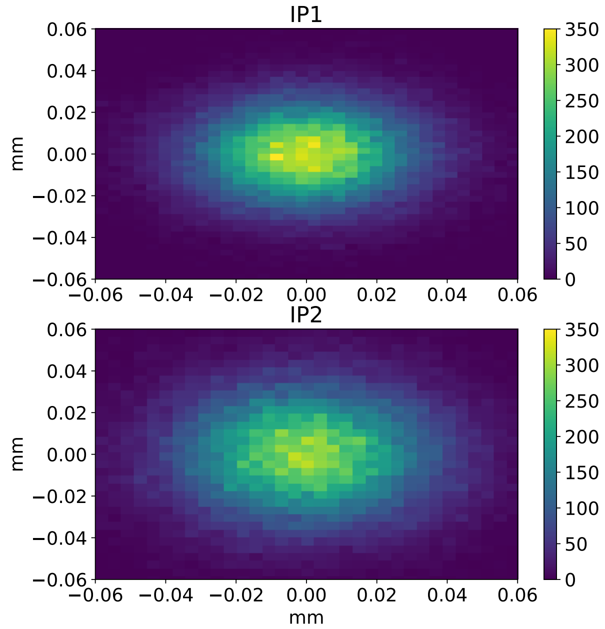


Figure 7: X-Y histogram of a Gaussian bunch consisting of 9000 particles at IP1 (top) and IP2 (bottom). The colinearity knob is set to +10 at IR2.

tool has also revealed unexpected sources of transverse coupling, such as long-range beam-beam. This was first seen in operation when the filling scheme was altered. This was then investigated during a dedicated MD where a change of the $|C^{-}|$ in the order of 2×10^{-3} was found [30]. From the measurements of the coupling throughout the cycle it has been very clear that it changes mostly at injection. The decay of the coupling at injection has been linked to the powering of the MCS, which has been investigated in MDs [31]. In order to prevent this drift, a different compensation scheme has been proposed. Instead of changing all the arcs with the same amount of b_3, the different arcs are changed by different amount in order to cancel the contribution to coupling while still correcting globally the same amount of b_3 [31]. This compensation scheme has been proposed for Run 3.

CONCLUSIONS AND OUTLOOK

The commissioning strategy has significantly changed during Run 2, going from a complete linear commissioning to a nonlinear. A lesson from 2015 is that the optics errors changed significantly during LS 1 and it is possible that a similar difference in the errors appears after LS 2. It would therefore be advisable to start the machine without any corrections applied.

In 2015 there were also issues with the orbit drifts due to movements of the IR8 triplet. This shows the importance of controlling and monitoring of the basic parameters, such as orbit, tune, and coupling, in order to have reliable and reproducible measurements. This is particularly important at the start up, when the machine has a tendency to be less stable.

The nonlinear correction strategy that has been adopted during Run 2 has proven itself very successful and will be the baseline also for Run 3. The best way to mitigate the effect of the higher-than-octupole feed-down is currently being investigated and will be added to the commissioning approach in Run 3.

The use of the developed linear coupling correction tool has significantly improved the control of the transverse coupling and, as a consequence, coupling-related instabilities have not been an issue in the LHC since it was started to be used in 2017 [29]. While this approach will continue to work in Run 3, an improved way to constrain the local coupling corrections at the IPs is needed. Additionally, requesting luminosity earlier on in the beam commissioning will be needed in order to fine tune and validate the corrections. It is also possible that we would, if not from the start of Run 3, need to optimize also the waist shift using luminosity [19]. It is therefore important to pursue the developments on these methods. A change in the compensation of the global b_3 decay at injection, which would be cancelling the drift in the transverse coupling, has also been demonstrated in MD's and is proposed for Run 3.

REFERENCES

[1] R. Tomás, *et al.*, "Record low beta beating in the LHC", *Phys. Rev. ST Accel. Beams* vo. 15, p. 091001 (2012).

[2] A. Langner and R. Tomás, "Optics measurement algorithms and error analysis for the proton energy frontier", *Phys. Rev. ST Accel. Beams* vol. 18, p. 031002 (2015).

[3] T. Persson, *et al.*, "LHC optics commissioning: A journey towards 1% optics control", *Phys. Rev. Accel. Beams* vol. 20, p. 061002 (2017).

[4] A. Langner et al., "Optics model," Proceedings of the 6th Evian Workshop, Evian, France, (2015).

[5] J. Wenninger, "Triplet movements and beam separation", presentation at HL-TCC 6th of May 2016.

[6] F. Carlier and R. Tomás, "Accuracy and feasibility of the β^* measurement for HL-LHC using K-modulation", *Phys. Rev. Accel. Beams* vol. 20, p. 011005 (2017).

[7] T. Persson, *et al.*, "Optics Controll in 2016", Proceedings of the 7th Evian Workshop, (2016).

[8] S. Fartoukh et al., "ATS MDs in 2016" CERN-ACC-2017—0003, (2017).

[9] A. Wegscheider, *et al.*, "Analytical N beam position monitor method", *Phys. Rev. Accel. Beams* vol. 20, p. 111002 (2017).

[10] E.H. Maclean, *et al.*, "A new approach to the LHC optics commissioning for the nonlinear era", accepted for publication in PRAB.

[11] E.H. Maclean, *et al.*, "Detailed review of the LHC optics commissioning for the nonlinear era", CERN-ACC-2019-0029, (2019).

[12] E.H. Maclean, *et al.*, "New LHC optics correction approaches in 2017", LHC Evian workshop 2017.

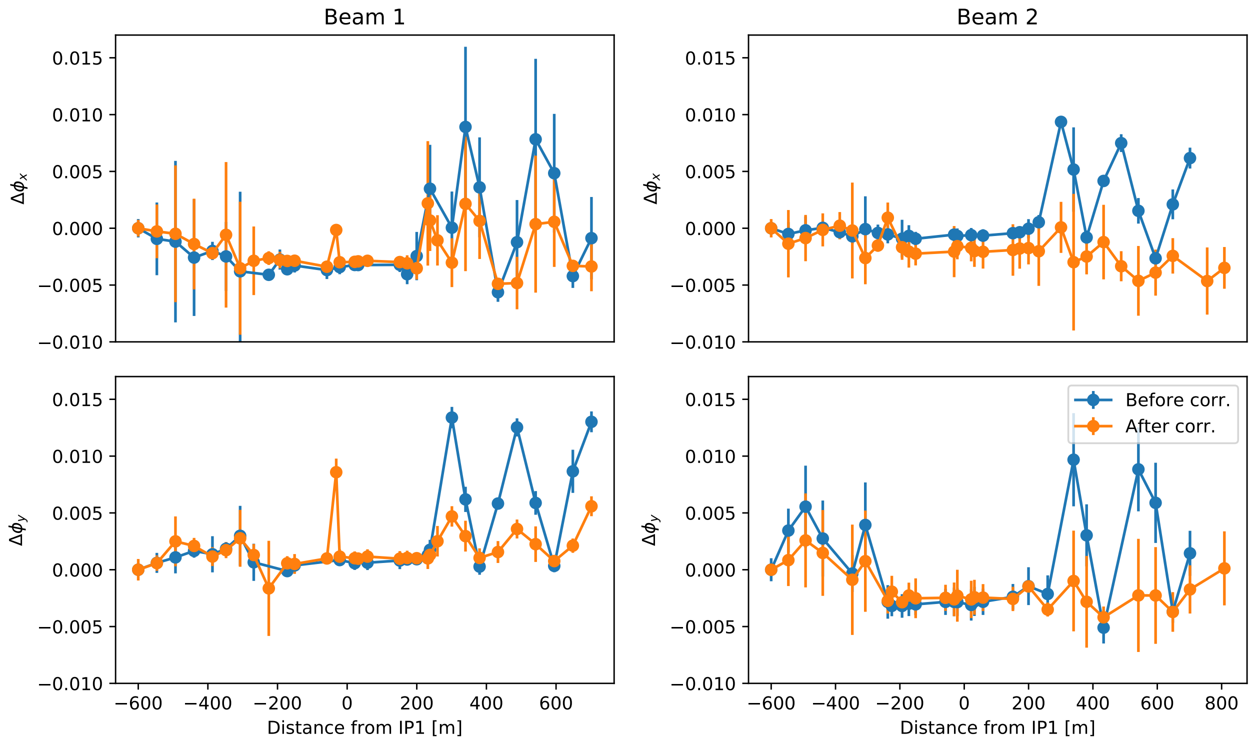


Figure 8: Propagating phase errors through IP1 before and after the refinement of the local correction.

[13] Dominik W. Wolf, Bachelor thesis: "Analysis of tune modulations in the LHC", CERN-THESIS-2018-25.

[14] R. Tomas , *et al.*, “LHC Run 2 Optics Commissioning Experience in View of HL-LHC”, presented at the 10th Int. Particle Accelerator Conf. (IPAC’19), Melbourne, Australia, May 2019, paper MOPMP033.

[15] F. Carlier, *et al.*, “Correction of skew octupoles with Resonance Driving Terms”, LMC 30 May 2018, `https://indico.cern.ch/event/733065/`

[16] F. S. Carlier, E. H. Maclean, T. Persson, and R. Tomas, “Nonlinear Correction Strategies for the LHC Using Resonance Driving Terms”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC’18)*, Vancouver, Canada, Apr.-May 2018, pp. 161–164. `doi:10.18429/JACoW-IPAC2018-MOPMF032`

[17] J. Dilly, *et al.*, “Report from LHC MD 3311: Amplitude detuning at end-of-squeeze”, to be published.

[18] E.H. Maclean, *et al.* “Linear and non-linear optics commissioning in 2018”, LMC 30 May 2018, `https://indico.cern.ch/event/733065/`

[19] J. Coello *et al.*, “New local optics measurements and correction techniques for the LHC and its luminosity upgrade”, to be published.

[20] S. Fartoukh, *et al.*, “LHC Beam experiments with telescopic flat optics in 2018”, to be published.

[21] T. Persson, *et al.*, “Investigation of the local coupling in IP2”, HSS Section meeting, 5th of December (2018). `https://indico.cern.ch/event/777370/contributions/3233595/attachments/1765852/2866984/IP2_luminosity.pdf`

[22] T. Persson, *et al.*, “MD4944: Local coupling measurement at the IPs”, to be published.

[23] T. Persson and R. Tomás, “Improved control of the betatron coupling in the Large Hadron Collider” *Phys. Rev. ST Accel. Beams* vol. 17, p. 051004 (2014).

[24] T. Persson, *et al.*, “Chromatic coupling correction in the Large Hadron Collider”, *Phys. Rev. ST Accel. Beams* vol. 16, p. 081003 (2013).

[25] L. R. Carver, X. Buffat, K. Li, E. Metral, and M. Schenk, “Transverse beam instabilities in the presence of linear coupling in the Large Hadron Collider”, Phys. Rev. Accel. Beams **21**, 044401, (2018)

[26] T. Persson et al., “Linear coupling dependence on intensity and a next step towards a feedback (MD1850)”, CERN-ACC-2017-0008, (2017).

[27] A. Calia, *et al.*, “Online coupling measurement and correction throughout the LHC Cycle”, in *Proc. ICALEPCS’17*, Barcelona, Spain, October 2017, paper TUPHA119, pp. 686-691.

[28] T. Persson, *et al.*, “Transverse Coupling Measurements With High Intensity Beams Using Driven Oscillations”, in Proc. 9th Int. Particle Accelerator Conf. (IPAC’18), Vancouver, Canada, Apr.-May 2018, pp. 208-211.

[29] X. Buffat, *et al.*, “Transverse Instabilities”, Proceedings of the 9th Evian Workshop (2019).

[30] J. Wenninger, *et al.*, “LHC MD2877: Beam-beam long range impact on coupling measurements”, CERN-ACC-NOTE-2018-0026.

[31] T. Persson, *et al.*, “LHC 3324: Counteracting coupling decay at injection”, to be published.