LHC OPTICS CORRECTIONS IN RUN 2

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 $\beta^*$, 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 developed 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 $\beta^*$ 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 $\beta^* = 60$ 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 $\beta$-functions from the phase advances. This new method provided better precision for the reconstruction of the $\beta$-functions than the 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 $\beta^*$ [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,
after obtaining a precise measurement of the $\beta$-function at the IP from K-modulation, the corrections could be constrained further and a control of the $\beta^*$ 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 $\beta$-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 $\beta$-beating with the crossing angles on was also applied to reduce the residual $\beta$-beating. The 2017 beam commissioning also profited from the new analytic N-BPM method to reconstruct the $\beta$-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 $\beta$-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 $\beta^*$ 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 $\beta$-beating from 2.0% for 30 cm to 2.5% for the 25 cm optics. The $\beta$-beating for Beam 1 at 25 cm is shown in Fig. 3.

The results from the K-modulation of the $\beta^*$ 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 $\beta^*$ 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 $\beta$-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 \(|K_0| = 0.008730 \text{ m}^{-2}\) 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.

<table>
<thead>
<tr>
<th>Circuit</th>
<th>(\Delta k) (10(^{-5})m(^{-2}))</th>
<th>Polarity</th>
<th>LSA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2012</td>
<td>2015</td>
<td>2016</td>
</tr>
<tr>
<td>IR1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ktqx1.l1</td>
<td>1.23</td>
<td>1.23</td>
<td>1.23</td>
</tr>
<tr>
<td>ktqx1.r1</td>
<td>1.0</td>
<td>-1.23</td>
<td>-1.23</td>
</tr>
<tr>
<td>ktqx2.l1</td>
<td>1.0</td>
<td>0.35</td>
<td>0.65</td>
</tr>
<tr>
<td>ktqx2.r1</td>
<td>-1.4</td>
<td>-0.7</td>
<td>-1.0</td>
</tr>
<tr>
<td>ktqx3.l1</td>
<td>1.22</td>
<td>1.22</td>
<td>1.22</td>
</tr>
<tr>
<td>ktqx3.r1</td>
<td>-1.22</td>
<td>-1.22</td>
<td>-1.22</td>
</tr>
<tr>
<td>kq9.11b1</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ktqx1.l2</td>
<td>2.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ktqx1.r2</td>
<td>3.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ktqx2.l2</td>
<td>+1.5</td>
<td>+1.5</td>
<td></td>
</tr>
<tr>
<td>ktqx2.r2</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-0.57</td>
</tr>
<tr>
<td>ktqx3.l2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ktqx3.r2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ktqx1.l5</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>ktqx1.r5</td>
<td>-2.0</td>
<td>-2.0</td>
<td>-2.0</td>
</tr>
<tr>
<td>ktqx2.l5</td>
<td>0.7</td>
<td>1.9</td>
<td>0.27</td>
</tr>
<tr>
<td>ktqx2.r5</td>
<td>1.05</td>
<td>1.9</td>
<td>1.48</td>
</tr>
<tr>
<td>ktqx3.l5</td>
<td>1.49</td>
<td>1.49</td>
<td>1.49</td>
</tr>
<tr>
<td>ktqx3.r5</td>
<td>-1.49</td>
<td>-1.49</td>
<td>-1.49</td>
</tr>
<tr>
<td>kq4.15b2</td>
<td>3.80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Measured \(\beta^*\) in 2017 commissioning and end of 2018 commissioning for the \(\beta^* = 30\) 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.

<table>
<thead>
<tr>
<th>IP 1 (\beta^*) [cm]</th>
<th>IP 5 (\beta^*) [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 1</td>
<td>Beam 2</td>
</tr>
<tr>
<td>H</td>
<td>V</td>
</tr>
<tr>
<td>2017</td>
<td>30.7 ± 0.2</td>
</tr>
<tr>
<td>2018</td>
<td>30.2 ± 0.1</td>
</tr>
</tbody>
</table>

Injection corrections linearly throughout the energy ramp. In 2017 a measurement of the optics at 2.5 TeV showed a smaller \(\beta^*\)-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 \(\beta^*\)-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).

<table>
<thead>
<tr>
<th>Circuit</th>
<th>(\Delta k \times 10^{-4} \text{m}^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2012</td>
</tr>
<tr>
<td>IR1</td>
<td>RQSX3.L1</td>
</tr>
<tr>
<td></td>
<td>RQSX3.R1</td>
</tr>
<tr>
<td>IR2</td>
<td>RQSX3.L2</td>
</tr>
<tr>
<td>IR5</td>
<td>RQSX3.L5</td>
</tr>
<tr>
<td></td>
<td>RQSX3.R5</td>
</tr>
<tr>
<td>IR8</td>
<td>RQSX3.L8</td>
</tr>
<tr>
<td></td>
<td>RQSX3.R8</td>
</tr>
</tbody>
</table>

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

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

Figure 4: Comparison of the \(\beta\)-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 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: MO\(F = -108\) A, MO\(D = 142\) A and for Beam 2: MO\(D = -70\) A, for \(\beta^* = 30\) cm and 6.5 TeV.
which re-balances the strength of the left and right MQSX,

Tab. 1. It was also observed that the local correction at IP1

very significant step compared to 80 cm in 2015. As a con-

pling in the IRs were initiated [21]. In Fig. 7 a 2D-histogram

effect in more detail simulations of the impact of strongcou-

the luminosity was recovered. In order to understand this

flat optics, while observing the luminosity. Using this knob,

trimming the colinearity knob [20], originally designed for

created about 50% reduction of the instantaneous luminosity

the optimal balance between the two correctors. The swap

strong local sources make it very hard to determine what is

there are only a few BPMs and the phase advance and the

advance between the two corrector magnets is such that the

left MQSX got swapped due to a human mistake. The phase

correction was given to linear coupling due to its link to transverse

used in operation in 2017–2018 [24]. In Run 2, additional fo-

instabilities [25]. A new method, based on using the ADT as

cus was given to linear coupling, which was then later

studied, such as chromatic coupling, which was then later

used in operation in 2017–2018 [24]. In Run 2, additional fo-

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 en-

abled 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.

2018 Ion Run

In 2018, the $\beta^*$ at IR2 was squeezed down to 50 cm: a

very significant step compared to 80 cm in 2015. As a con-

sequence, 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 uncor-

rected phase error, but we can observe that the situation was

clearly improved.

The new local coupling corrections for IP2 were calcu-

lated 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 cou-

pling 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 ver-

tical 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 hu-

man 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 be-

tween 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 $\beta^*$ measurement with K-modulation

is small as seen in Tab 5.

CONTROL OF GLOBAL COUPLING

The development of systematic global coupling correc-

tions 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 fo-

cus 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 en-

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

Table 5: Measured $\beta^*$ from beam commissioning and the MD for different crossing angles and colinearity knobs settings. The colinearity knob is defined as $MQXS.3L_2 = 10^{-4}$ m$^{-2}$ and $MQXS.3R_2 = -10^{-4}$ m$^{-2}$. There are no measurements of Beam 1 during the MD since the beam was lost already during the ramp.
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.

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

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


