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OPTICS CORRECTION STRATEGY FOR RUN 3 OF THE LHC

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Abstract

The Run 3 of the LHC will continue to provide new challenges for optics corrections. In order to succeed and go beyond what was achieved previously, several new methods to measure and correct the optics have been developed. In this article we describe these methods and outline the plans for the optics commissioning in 2022.

INTRODUCTION

The correction strategy planned for Run 3 has significantly evolved since the first optics corrections in the LHC in Run 1 [1]. In Run 1 the Interaction Region (IR) corrections were based on the phase advance measurement obtained from the Turn-by-Turn (TbT) measurement and only linear corrections were considered. In Run 2 K-modulation measurements were used to better constrain the correction and the nonlinear corrections up to octupolar components were implemented and used in normal operation [2,3]. Coupling control was significantly improved in Run 2 with a better theoretical understanding and the new method utilizing the damper (ADT) to drive a forced oscillation, in a similar manner to the AC-dipole [4,5]. A challenge in Run 3 compared to Run 2 is the increased number of optics configurations that will be used to deliver luminosity. In this article we outline developments that will be important to successfully correct these optics configurations.

CODE DEVELOPMENT

The optics measurements and correction (OMC) software aims at enabling accurate and efficient beam-based optics measurements and corrections online. The software's main purpose is to analyse the TbT data from the Beam Position Monitors (BPM) in order to calculate beam optics parameters. During Run 2, a CERN developed framework [6,7] was extensively used and played a large part in the successful optics corrections in the LHC. The main structural philosophy is placing the analysis algorithms in a Python suite and viewing its results in a Java GUI [7], compatible with the LHC Software Architecture (LSA) [8]. Over time, the software became increasingly difficult to maintain and extend. Recently we thoroughly reviewed, extended, and consolidated the codebase, leading to a more maintainable and portable project built on Python 3.7 and modern scientific libraries, such as NumPy [9]. The development has lead to a new analysis framework omc3 [10], which uses harmonic analysis [11] that is significantly faster than the previously used [12]. Omc3 aims, when possible, to be accelerator-independent, which makes it easier to extend to other accelerators. Figure 1 shows the increase in speed to perform a full analysis of measurement in the LHC and how the number of lines of code have shrunk versus time. The points in 2017 and 2018 show intermediate development steps in the old codebase, while 2020 shows omc3.

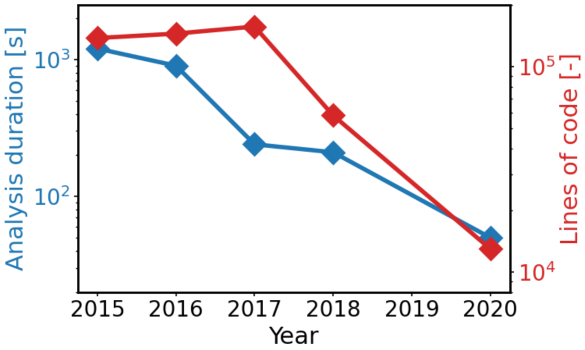

Figure 1: Time to perform a full analysis of measurement in the LHC and the number of lines of codes.

Machine Learning (ML) techniques to remove malfunctioning BPMs have already successfully been applied to Run 2 data [13]. The exploration of ML techniques to filter tune measurements, reduce noise and to find optics corrections will be pursued in Run 3 [14–18].

K-MODULATION AND β^*

It has been observed that the accuracy of the β^* measured with K-modulation is limited when the distance from the modulated quadrupole to the IP is close to the value of the β^*. An example of such an optics is the the Van der Meer optics which is used to calibrate the luminosity measurements. In order to overcome this issue a new method that also considers the measured phase advance when reconstructing the β^* has been developed [19]. A simulated comparison when the phase measurement is included in the reconstruction is compared to the traditional method in Fig. 2. In the simulation a tune noise of 5×10^{-5} was considered. We notice that the outliers completely disappear when the phase advance is used in the reconstruction of the β^*. An alternative way to measure the β^* is to obtain the β-functions from the amplitude of the TbT oscillations. To improve the BPM calibration, crucial to reconstruct the β^* by this method, two beam-based methods will be investigated [20,21].

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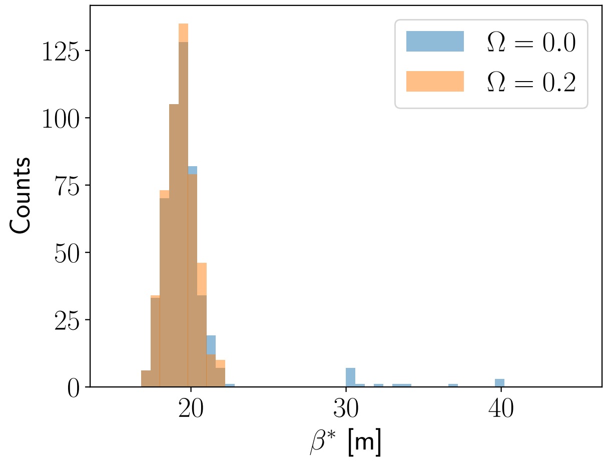

Figure 2: K-modulation simulation showing the improvement from combining the phase information with the modulation data when reconstructing the β^*. The Ω is the relative weight giving to the phase information in the reconstruction. The correct $\beta^* = 19$ m.

IR CORRECTIONS

The Segment-by-Segment technique (SbS) has been used to correct the local errors in the IRs since Run 1 [1]. An alternative approach is to use the Action Phase Jump (APJ) method to find corrections [22, 23]. The idea is that a deviation from the model will show up as a jump in the action phase. This method has been investigated via simulations for the Run 2 optics with a β^* of 40 cm. The APJ method performed better than the SbS when large errors in the matching quadrupoles close to the IR were assigned, seen in Fig. 3. In cases where smaller errors were applied the performance between the two methods were similar [24]. In Run 3 we plan to utilize both methods and also combine them with information from K-modulation and ML in order to find the best possible corrections.

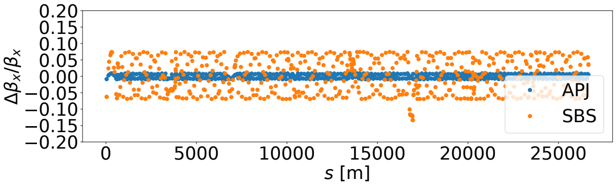

Figure 3: The residual β-beat for the horizontal plane after correction with the SbS technique and the APJ for a simulation with large quadrupolar errors in the matching regions of IR5.

COUPLING CONTROL

The coupling corrections will be done in several steps. First, there will be a local coupling correction based on the coupling Resonance Driving Terms (RDTs) f_{1001} and f_{1010} [25]. However, there will still be an uncertainty in how to balance the skew quadrupoles left and right of the two low β^* IPs. In order to find the best balance, which has an impact on the beam size, a new method is under investigation. It breaks the symmetry of the IR by creating a rigid waist shift for both beams and planes at the IP. In this way the local coupling error at the IP will also cause a change of the global coupling, which is significantly easier to measure [26, 27]. The correction can be refined with a scan of the strength of the skew quadrupoles while observing the luminosity. It is also likely that we will need to apply an arc-by-arc correction to remove any structure of the f_{1001} in the arcs. In particular these corrections will profit from the newly developed formalism to model the effect of forced oscillation on the coupling RDTs [28]. Figure 4 shows a comparison of the reconstructed forced coupling RDT f_{1001} by the methods currently used in LHC (*rescaling* and *analytical*) and a formula developed with the new formalism (*new analytical*). The curve *model* represents the reference case of uncompensated forced coupling as measured using TbT data. The figure demonstrates that the new formalism is able to reconstruct the measured coupling considerably better than the previous methods.

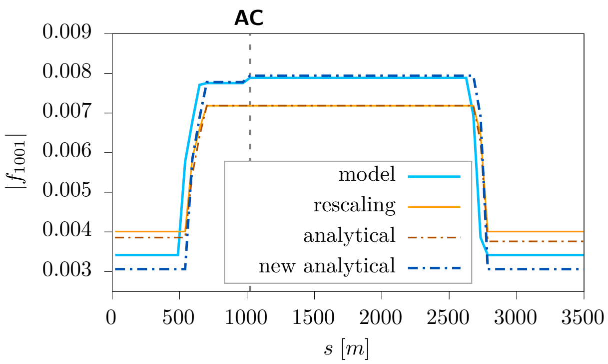

Figure 4: Comparison of a new, improved formula to model forced oscillation for coupling measurements. The new formula can well reconstruct the jump in the amplitude of f_{1001} at the position of the AC-dipole.

In Run 2 a method to excite the beam using the ADT in a similar fashion to the AC-dipole was developed [29]. The benefit is that it can act on individual bunches, and hence can also be used when many bunches are present in the machine. This method has proven successful, but it has also been observed that the measurement is less accurate, in cases of low levels of coupling and high levels of noise. The larger noise comes from the fact that the excitation with the damper is significantly lower compared to the AC-dipole, making the signal-to-noise ratio worse.

The analytical methods are more precise in reconstructing the free RDTs but they are also more sensitive to noise than the scaled compensation. This can be understood by the fact that the analytical methods are relying on a few measurement points close to the AC-dipole to calculate the compensation. As a result when the noise is approximately 50% or more compared to the signal the corrections based on the analytical method are significantly worse [30]. The upper plot in Fig. 5 shows a case with noise level comparable to the AC-dipole and in this case the residual after correction is

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more similar between the two methods and well within the target of correcting the $|C^-|$ to below 10^{-3}. As seen, this is not always the case for the analytical compensation in the lower plot which approximately corresponds to a noise level when the beam has been excited with the damper.

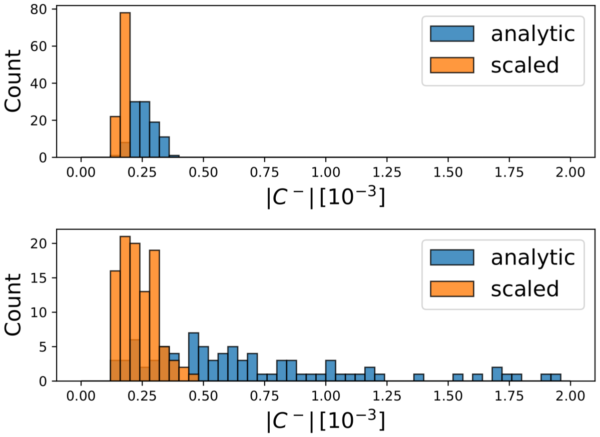

Figure 5: Simulation showing the residual $|C^-|$ after a coupling correction for the analytical method and the scaled. The initial coupling was 4.4×10^{-3}. The upper plot shows the results with a noise level comparable to what is observed with the AC-dipole while the lower shows results with a noise level which approximately corresponds to an ADT excitation.

The transverse coupling has been observed to drift at the injection setting of the LHC. This has been linked to the powering of sextupolar correctors attached to every dipole (MCS), used to compensate the dynamic decay of the sextupolar components of the LHC dipoles (b_3). This dynamic compensation is used to keep the chromaticity constant during the injection phase. However, this compensation has, in combination with vertical feed-down, been observed to cause a change in the transverse coupling. In order to counteract this a modified approach is proposed to be used in Run 3. It compensates the same dynamic change of b_3 but distributes it differently between the arcs to keep the coupling constant [31]. This was tested by applying the uneven change of the MCS, corresponding to approximately two hours of b_3 decay, and measuring the wanted change in chromaticity while observing an impact to the coupling of only a few 10^{-4}. The measured change to coupling as a function of time at injection together with the predicted change with the proposed compensation is shown in Fig. 6.

NONLINEAR STRATEGY

Run 2 has shown that the corrections of the nonlinear errors in the IRs are crucial in order to achieve the expected Landau damping. Due to feed-down, the corrections are also important to control the linear optics parameters such as β-beat and transverse coupling. When the octupolar correction was implemented in Run 2 the signal-to-noise ratio of the online tune measurement system (BBQ) was enhanced [3]. This in turn facilitated other measurement throughout the commissioning. It is therefore planned to start with the previous octupolar correction and then later re-iterate in order to establish a better correction. The octupolar and sextupolar corrections will be based on a scan where the crossing angle is changed and the feed-down to tune and coupling is measured. The skew octupolar corrections will also be based on driven RDTs [32]. Uncorrected sextupolar errors in the IR will lead to β-beating through feed-down and change of the transverse coupling. Correcting this effect is of extra importance in case the crossing angles are changed during operation since the feed-down would also change.

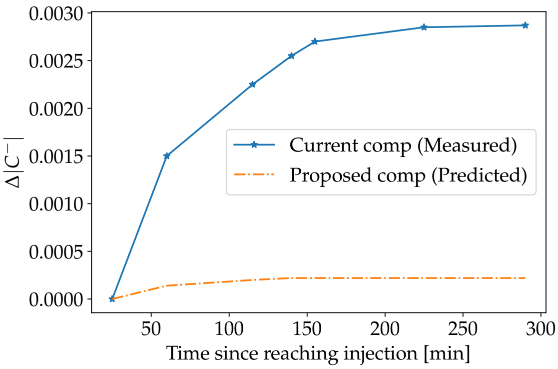

Figure 6: The blue line shows the measured change in transverse coupling as a function of time since the injection plateau was reached and in orange is the predicted change when the dynamic part of the b_3 decay is corrected unevenly between the arcs.

In 2018 it was observed that the amplitude detuning was changed when a crossing angle was applied. This indicates that higher orders are feeding down to octupolar. At low β^* this has a significant impact on the footprint. The exact multipolar order responsible for this will be investigated in Run 3 both through additional crossing angle scans in the IRs where we measured the feed-down to tune and coupling and possibly through driven RDTs. A correction of the b_6 based on these measurement will be explored.

CONCLUSION AND OUTLOOK

The time between Run 2 and Run 3 has been used to further develop our methods to pave the way for a successful optics commissioning in 2022. It is worth remembering that the optics errors in Run 2 were significantly different compared to Run 1, and it is possible that the errors in Run 3 again will be different. It is also likely that we will face new unforeseen challenges in Run 3. It is therefore important to have a codebase that is easily extendable in order to quickly implement new methods to overcome potential issues. Run 3 will also work as a testbed for the even more challenging optics corrections needed for the HL-LHC.

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