OPTICS CONTROL IN 2016

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Abstract

In 2016 the β-functions at the interaction points of ATLAS and CMS have been squeezed down to 0.4 m. This is below the design $\beta^* = 0.55$ m at 7 TeV and has been instrumental to surpass the design luminosity. Even though the β-beating for the virgin machine was above 100% the corrections reduced it to an rms β-beating below 1% at the two main experiments and below 2% rms around the ring. These results are presented together with the β-beating deriving from the crossing angles in combination with the sextupolar errors in the IRs. A way to correct the errors using sextupolar correctors is referenced and how this could be integrated in the commissioning is outlined. Furthermore, the progress towards an automatic coupling correction is described.

INTRODUCTION

A lot of progress to improve the control of the linear optics has been done since the first optics commissioning in 2009 [1–5]. A better understanding of the non-linear magnetic errors has also been obtained. This includes studies and correction of chromatic coupling [6], non-linear coupling [7, 8], amplitude detuning [9], nonlinear chromaticity [10], and higher order errors in the Interaction Regions (IRs) [11]. This is an area which will continue to grow in importance as the LHC enters a more challenging regime with an even lower β^*.

During the proton run in 2015 a systematic offset of the waist of in IP1 and IP5 was measured [12–14]. This lead to a new correction strategy that was used during the 2016 commissioning. This significantly improved the control of the β^*. It was, however, observed in simulations and indicated from measurements that the change of crossing angles have an impact on the β-beating. In this article we outline the request for the 2017 beam commissioning, which also include a correction of this effect. Furthermore, we discuss the plans for a new automatic coupling corrections tool.

Systematic offset of the β^*

In 2015 it was discovered that there was a systematic offset of the β^* waists in both IP1 and IP5 resulting in an increase of the β^*, causing about 5% luminosity loss [12, 13]. From the measurements of the 2015 waist we clearly observe a systematic offset of the position of the waist in the direction of the focusing quad and about 10% β-beating. This was unexpected since the estimates of the magnetic error were unlikely to create such an offset. The assumptions of the gradient uncertainties were based on WISE [15, 16], which provides smaller uncertainty values than [17]. In order to estimate whether the measured errors are compatible with the corrections a test of the significance was done. The assumption is that the corrections from 2016 are reproducing the errors. Using this as an input we performed a z-value test [18], which showed that it was less than 0.04% chance that the errors are following a normal distribution with 0.11% as standard deviation and 0 as mean error. This suggests that the optics errors in the IRs are not well represented by the given RMS uncertainty in the triplet quadrupoles. The propagation of the β-function from the turn-by-turn measurement propagated to the Interaction Points (IPs) would give an accurate β^* if quad errors are below 0.04% RMS as expected in [15]. Offsets of the waist of the β-functions are also important to avoid since it may reduce the available aperture. Furthermore, we also investigated the impact of a longitudinal misalignment of the triplet magnets with an RMS of 6 mm. The result shows that the impact is in the order of a few percent and hence is too small to explain explain the discrepancy.

2016 COMMISSIONING

The problem with the systematic β-function waist offset led to integrate the K-modulation measurements in our calculations. The K-modulation [19, 20] is performed using the two most inner magnets close to the IP. This provides a measurement of the β-function in the entire drift space between the two magnets. The β-function evaluated at the location of the two most inner BPMs are used for the correction tool. Already during the ion optics commissioning in 2015 additional corrections were performed to mitigate this issue [14]. After this experience, the tool for K-modulation measurements was fully automatized to obtain the result on-line [20–22], which then could be used in the corrections. The details of this improved procedure and corrections are described in the following sections.

Improvements in K-modulation Measurements

The K-modulation method has been used to measure the β-functions at the interaction points. The average β-functions in the triplet quadrupoles left and right of the IP can be calculated by measuring the tune changes resulting from a gradient modulation in the quadrupole, as described in [19, 21, 23]. The optics functions are then interpolated towards the IP, thus providing measurements of β^* and the position of the waist. The online implementation of the K-modulation tool allows for a faster and more accurate measurement of the β^*.

K-modulation measurements are done at injection tunes ($Q_x = 64.28$, $Q_y = 59.31$) which are further away from third order and coupling resonances than the collision tunes ($Q_x = 64.31$, $Q_y = 59.32$).

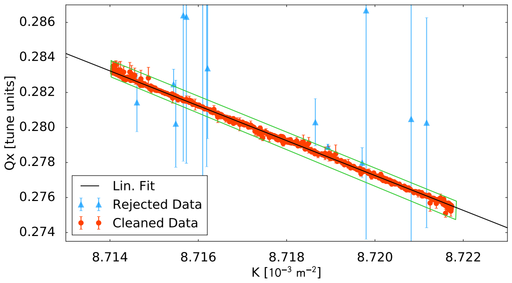

Figure 1: Linear fit of horizontal tune data for beam 2 with a illustration of the data cleaning process.The rejected data is shown in blue. An online tool is used to specify the domain of acceptance shown in green.

A cleaning tool has been developed to clean outliers in the tune data online. The domain of acceptance is determined by tracing a parallelogram around the desired data. Figure 1 shows the horizontal tune data for beam 2 obtained after a modulation of the quadrupole left of IP1. The cleaned data, inside the domain of acceptance, is shown in red while the rejected data is shown in blue. This has been a crucial ingredient to clean efficiently the data in short time periods and hence obtain accurate results within the time scale of a minute.

The errors in the tune data are determined as a quadrature of the tune precision ($2.5 \cdot 10^{-5}$) and the standard deviation resulting from the binning of the BBQ [24] data. The binning is necessary due to the lack of synchronization between the tune data and the quadrupole current data. Linear fits of the data provide accurate $\frac{\Delta Q}{\Delta K}$ measurements, as presented in Fig. 1. The typical uncertainty of the fit is between 0.6 m^2 and 1 m^2.

Local Corrections

Local corrections are applied around the IPs where the magnets are individually powered [2]. The idea is to reconstruct the initial conditions at a location outside the IP and then propagate the optics parameters through the lattice as if it were a beam line. The correction is evaluated for both beams and tested for several optics with larger β^*. Furthermore, since 2016 the β-functions obtained from the K-modulation are also included in the segment-by-segment technique. Figure 2 shows how the 2015 and 2016 correction both correct the phase beating but it is only the 2016 correction that is able to reproduce the β-function close to the IP. This illustrates why it was only the corrections applied in 2016 that were able to correct the waist shift.

In the case of well calibrated BPMs it is possible to reconstruct the β-functions from the amplitude of the oscillations [25, 26]. The plan was to use the ballistic optics where the triplets were turned off to calibrate the BPMs and then use them with the new calibrations in the calculation of the local corrections. However, the method was not accurate enough to provide a good constraint on the correction but was important for debugging the new K-modulation software.

Global Corrections

The local corrections reduced the β-beating to a peak of about 20%. However, to reach a lower β-beating a global correction approach is needed. This is needed since not all the errors are originating from the IRs. The better corrections also provide more margin for other errors in the machine and reduce the luminosity imbalance to a minimum between the experiments. The correction is based on a response matrix approach. The correction method was improved in 2016 by taking the measurement uncertainties into account as weights [27].

By including the results from K-modulation the β-functions at the IP are better corrected, this way minimizing the luminosity imbalance between experiments. In order to find a good trade-off among the observables, corrections are evaluated before they are applied to the machine. The evaluation consists of corrector strengths checks as well as of a prediction of the optics parameters after the correction. This in turn may serve as a figure of merit for the correction weights optimization.

Results from 2016 commissioning

After the local and global corrections have been applied in 2016 a final set of measurements with the AC-dipole and K-modulation were taken. As a result of the previously mentioned improvements an unprecedented rms β-beating below 2% was achieved in 2016. Figure 3 shows the β-beating for both beams at β^* of 40 cm. The final results have been filtered from malfunctioning BPMs. The filtering was done through removing faulty BPMs using the SVD and removing the BPMs with too high noise levels [28, 29]. Finally, also a few BPMs were removed since they were not synchronized correctly.

EFFECT OF CROSSING ANGLES

The optics commissioning was done without crossing angles in order to maximize the available space for beam excitation. However, the optics was re-measured in June with the crossing angles on. The differences were found to be small and were not impacting the safety of the LHC operation. The discrepancy was, however, still in the order of a few percent. It should also be noted that there were a few months between the two measurements which might also have had an impact. However, the other measurements we have observed with the exact same configuration, with month in between, shows a smaller effect. This indicates that parts of the increase is linked to the crossing angles. The results of a few percent of β-beating is also consistent with predictions from simulations [30]. It is therefore likely that the main part of the difference is deriving from the change in crossing angles. A b_3 error together with a horizontal offset

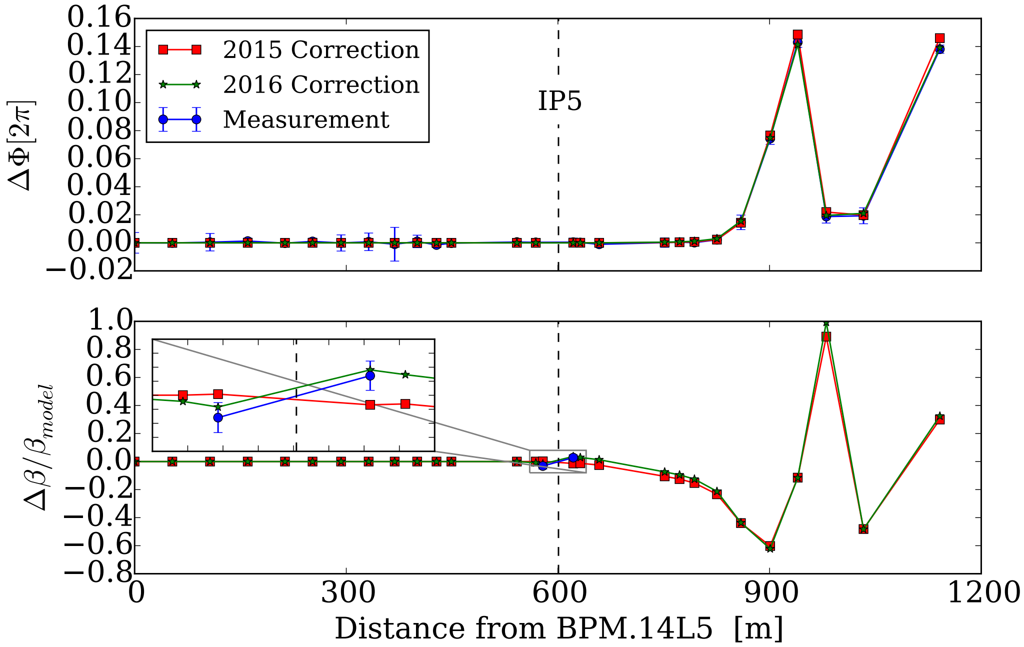

Figure 2: A comparison between how well the 2016 and 2015 corrections would correct the phase error (top) and the local β-beating (bottom). Note that both the lines and points show the deviation from the ideal model.

feeds-down to a quadrupolar field and hence changes the β-beating. The effect is the same for an a_3 error combined with a vertical offset.

COUPLING CORRECTIONS

In 2016 there were several observations of coupling changes. A decay-like change of the coupling was first observed in operation and then measured in a MD [31]. There has also been changes of the coupling at different points throughout the cycle. The change in coupling can derive from several sources such as feed down from higher order, with an orbit change or other types of movements. Using measurements of the change of tilt of the quadrupoles it is possible to predict that change in coupling [32]. The results are shown in Fig. 5. As the β^* is squeezed further this effect will enhanced. It has been observed that the BBQ is not reliable for coupling measurements, in particular, for small β^*. The method that has been demonstrated to be reliable is to make a coherent driven oscillation of the beam and based on this calculate a correction. In 2016 we demonstrated a correction resulting in below a per-mil of transverse coupling [5] using the AC-dipole. This is the lowest level of coupling ever measured in the LHC. The use of the AC-dipole is limited to low intensity beams. In order to address this limitation the ADT has been equipped with an AC-dipole like excitation. This enables to excite only one bunch even in case the machine is filled with many trains. The data can then be recorded with both the normal BPMs and the DOROS BPMs [33]. This was successfully demonstrated during MDs [31, 34]. The goal for 2017 is to make this into an fully operational tool that can be used by the operators to correct the transverse coupling online.

2017

The time needed for the 2017 commissioning will depend on the optics configuration chosen. In case the optics is left unchanged only a re-validation is needed. In case it is decided to commission a new optics a total of 3 shifts are needed for the linear optics. The decision to select nominal or ATS optics will not influence the number of shifts needed for optics corrections.

The non-linear optics commissioning is estimated to need two shifts [30]. The goal is to remove the effect of the crossing angle on the β-beating.

Additional requests are to have 1 shift distributed over the commissioning to test the automatic coupling correction. In order to progress with the β from amplitude [25] half a shift would be needed.

Figure 6 shows the planned commissioning for 2017. The blue part is the linear part of the comissioning and is the same as in the 2016 commissioning. When it is finished it is possible to start with other commissioning activities and when convenient in the schedule continue with the non-linear commissioning of the IR sextupoles correction.

The experience gained in 2016 has shown that the combined ramp and squeeze does not pose an obstacle in reaching a good optics correction. The optics correction will therefore not set a limit on the available reach with the ramp and squeeze in 2017.

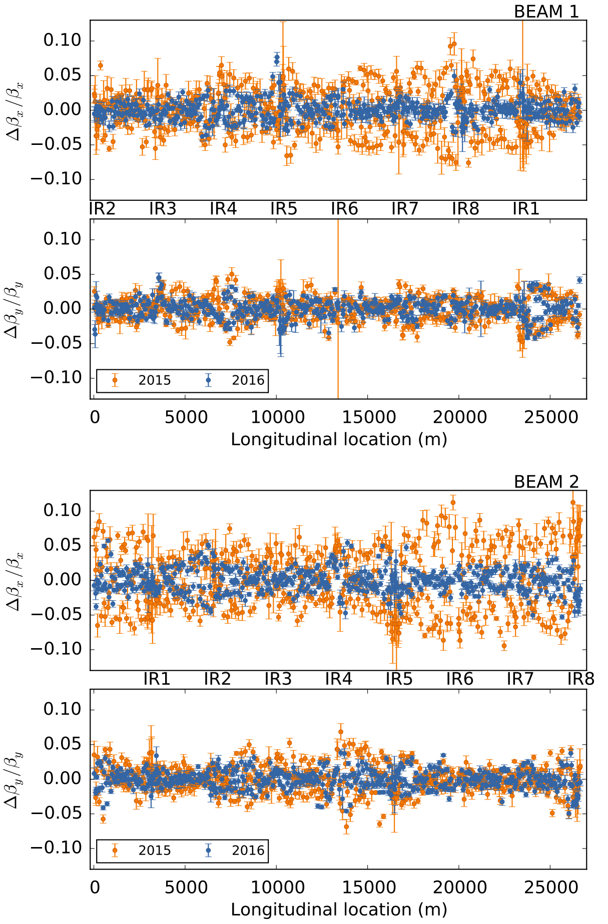

Figure 3: β-beating at 40 cm β^*

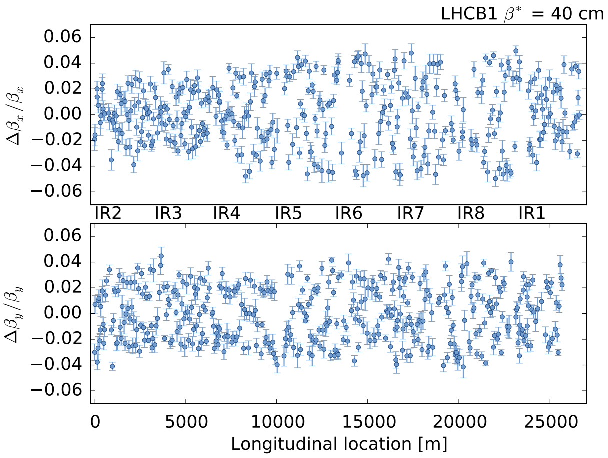

Figure 4: Relative difference between the optics measurement in commissioning without crossing angles and the measurement in June when the crossing angles were on.

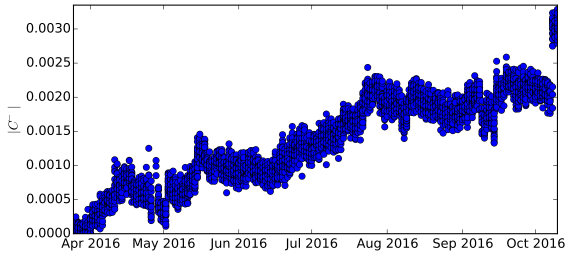

Figure 5: The predicted transverse coupling from the tilt of the IR1 and IR5 triplet. The position is measured once every hour.

CONCLUSIONS

The LHC optics has been successfully commissioned down to β^* of 0.4 m at 6.5 TeV, which is lower than the design value of 0.55 m at 7 TeV. This is the lowest operational β^* used in the LHC and hence the most challenging configuration so far. Even so an unprecedented β-beating in a high energy proton collider has been achieved. These results have only been possible due to the recent improvement in obtaining β-functions on-line from the K-modulation, the incorporation of theses results in the local and global corrections, the use of appropriate weights on the different optics parameters, the longer AC-dipole plateau, the N-BPM method and the reduction of the orbits drifts from the quadrupole movements. The effect deriving from the sextupolar errors in the IRs in combination with crossing angles is proposed to be corrected in 2017. This should help reducing the β-beating further for the operational beams.

ACKNOWLEDGMENTS

We greatly thank all LHC Machine Coordinators, Engineers In Charge, and the operation crew for their continuous support during the optics commissioning. The authors also would like to thank Riccardo de Maria and Massimo Giovannozzi for fruitful discussions.

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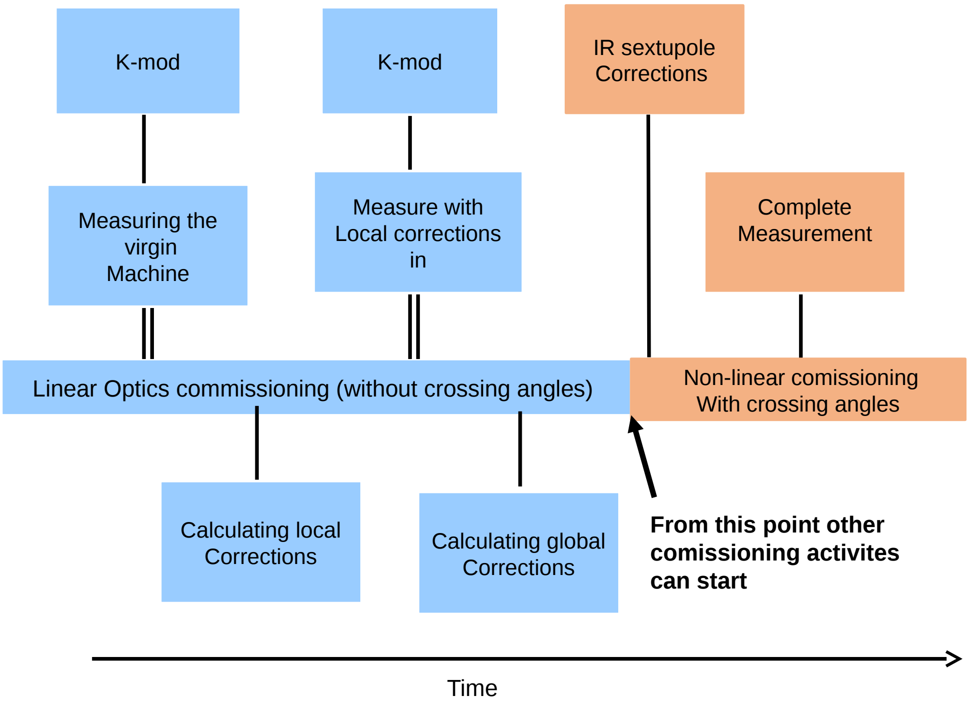

Figure 6: The proposed schedule of the optics commissioning in 2017. The blue part is the linear commissioning and is the same as in 2016. The yellow part is the non-linear commissioning and can be done in parallel with other commissioning activities.

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