LHC optics commissioning: A journey towards 1% optics control

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Since 2015 the LHC has been operating at 6.5 TeV. In 2016 the β-functions at the interaction points of ATLAS and CMS were squeezed 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 of 10^{34} $\mathrm{cm^{-2}\,s^{-1}}$. Achieving a lower than nominal β^* has been possible thanks to the extraordinary performance of the LHC, in which the control of the optics has played a fundamental role. Even though the β-beating for the virgin machine was above 100%, corrections reduced the rms β-beating below 1% at the two main experiments and below 2% rms around the ring. This guarantees a safe operation as well as providing equal amount of luminosity for the two experiments. In this article we describe the recent improvements to the measurement, correction algorithms and technical equipment which allowed this unprecedented control of the optics for a high-energy hadron collider.

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I. INTRODUCTION

The 2012 optics commissioning of the LHC reached a new record low β-beating for hadron colliders [1]. Since then, many improvements have been made to equipment, algorithms and analyses to further reduce the errors and uncertainties of the optics measurements and corrections. Improvements to the reconstruction of both β-functions and transverse coupling from turn-by-turn (TbT) data have been made [2,3]. In 2016 dedicated coupling corrections in the LHC brought the closest tune approach to about 2×10^{-4} [4]. This is the lowest level of coupling ever measured in the LHC.

A new online K-modulation application has also been developed, which enables direct measurement of the β^* [5]. It is very important to provide the two main experiments with the same amount of luminosity and hence the same discovery potential [6]. A better understanding of the nonlinear magnetic errors has also been obtained. This includes studies and correction of chromatic coupling [7], nonlinear coupling [8,9], amplitude detuning [10], nonlinear chromaticity [11], and higher order errors in the interaction regions (IRs) [12]. This is an area which will continue to grow in importance as the LHC enters a more challenging regime with an even lower β^*, however the focus of this article is the improvements which enabled the achievement of the 1% control of linear optics in the LHC.

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The optics configuration in the LHC is normally referred to by the β^* at the ATLAS and CMS experiments, located in Interaction Point 1 (IP1) and IP5. In 2012 the LHC operated at a β^* of 0.6 m. When the machine was restarted in 2015 this was increased to 0.8 m and in 2016 it was reduced to 0.4 m. This change to the operational configuration makes optics correction even more challenging since the imperfections in the IRs are responsible for a large part of the overall deviation from the design optics [1]. The low β^* is one of the ingredients that has enabled the LHC to reach 1.5×10^{34} $\mathrm{cm^{-2}\,s^{-1}}$ which is 50% above the design value [13,14].

In this paper we describe the changes that have been made since 2012 to obtain an rms β-beating below 1% in the two general purpose and high luminosity experiments. Section II presents the improvements done to the 2015 commissioning and the factors that were limiting the corrections. In 2015 a systematic offset of the longitudinal β-function waist in IP1 and IP5 was discovered which led to a new correction strategy described in Sec. III. The new method incorporated the results from the online K-modulation to further constrain the corrections [5]. Furthermore, the improvements in methods and procedures to obtain the unprecedented low-level β-beating for a high energy collider are described. The result from the optics measurements, after corrections, are presented in Sec. IV. In Sec. V we discuss how the global corrections perform at different configurations and what impact this might have on the foreseen β^*-leveling.

II. 2015 COMMISSIONING

LHC optics commissioning in 2015 took place after more than two years of shutdown, referred to as

Long Shutdown 1 (LS1). The optical configuration featured $\beta^* = 80$ cm at IP1 and IP5. Several improvements were implemented in preparation for this commissioning with the aim to further reduce the error and uncertainty of the optics. A new method to calculate β-functions from the phase advances between beam position monitors (BPMs) had been developed. The previous method used 3 BPMs [15] while the new N-BPM method [3] uses 11 BPMs in the case of the LHC. The BPMs are chosen to have favorable phase advances for the reconstruction of the β-function. This significantly reduces the error bars on the measured β-functions and provides a more accurate estimate of the uncertainty.

The local model used to reconstruct the β-function has also been improved thanks to the ability to read the exact settings of the tune corrector magnets [16,17]. This is important since reconstruction of the β-function relies on the local model.

The AC dipole was upgraded during LS1 to be able to excite the beam for 6600 turns compared to the 2200 before the shutdown. A study of the stability of the AC dipole showed that the horizontal plane for beam 1 had a less stable excitation frequency. Furthermore, an orbit drift disturbing the dispersion measurements is also described in this section. Finally, the measured systematic offset of the β^*-waist in the IPs during 2015 is described.

A. AC dipole performance

The AC dipole creates a coherent betatron oscillation around the closed orbit. This enables beam excitation without emittance increase [18]. The increased length of the TbT data allows investigation of optics stability during one beam excitation. To study potential changes over time the measurement files of 6600 turns were analyzed in parts of 2000 turns each. Noise reduction using the singular value decomposition (SVD) technique [19] was performed for each 2000 turns window separately to avoid additional correlation. This enables the study of the time evolution of observables like the driven and natural tunes in both planes as well as the phase advances between BPMs. Figure 1 shows the evolution of the reconstructed driven tune over time for beam 1 in the horizontal plane. An increase of the driven tune by 10^{-6} can be seen in the horizontal plane for data sets which start from turn number 1000 to 2000. This behavior is not seen in the vertical plane or in any plane for beam 2. It is furthermore visible for different measurement days and different optics. No such behavior is seen for the natural tunes of the machine. Therefore this is assumed to be an artifact produced by imperfection of the AC dipole. Figure 2 shows how the phase advance uncertainty depends on the number of turns analyzed. For the horizontal plane of beam 1, where the measured AC dipole tune unexpectedly changes between turn number 2000 to 3000, the uncertainty on the phase advance also increases with larger numbers of turns analyzed.

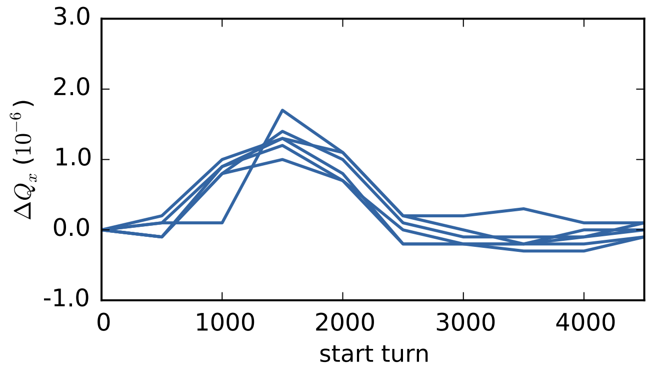

FIG. 1. Measured deviation of the AC dipole horizontal beam 1 tune when 2000 turns out of 6600 were analyzed, starting from different turn numbers. The plot shows six different measurements at a β^* of 80 cm. This bump was not visible for the other plane or beam and has been fixed by replacing the amplifier of the beam 1 AC dipole.

Figure 3 shows the distribution of the phase advance uncertainties for measurements from 2012 (where up to 2200 turns of TbT data were recorded) compared to 2015 (with 6600 turns of TbT data). A rms phase noise below 10^{-3} has been achieved since 2015. The longer TbT data acquisition improves the precision of the measured phase advances. Moreover, a significant difference in the uncertainty is visible for the different planes. This can be attributed to the aforementioned technical issue with the AC dipole in combination of a tendency to excite less in the horizontal plane. This has recently been solved by replacing the amplifier of the beam 1 AC dipole.

B. Orbit drifts

In 2015 orbits were subject to fast drift with periodicity of approximately 8 h [20] due to the movements of the triplet quadrupoles in IP8. This significantly reduced the accuracy of dispersion measurements. This in turn had a negative impact on the performance of the global

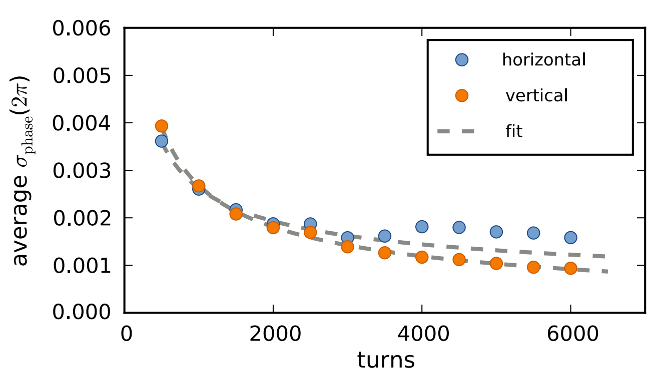

FIG. 2. Average precision of the measured phase advance for different number of turns used in the analysis for beam 1. The fit function is $\alpha/\sqrt{x}$, and for the horizontal plane only the first five data points were used for the fit.

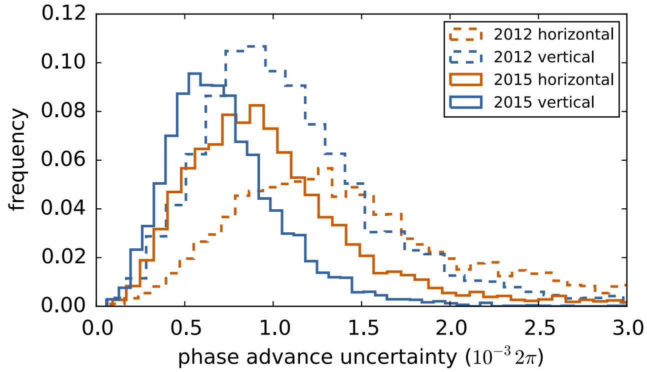

FIG. 3. Uncertainties of the measured betatron phase advances for both beams for optics with $\beta^* = 60$ cm (2012) and $\beta^* = 80$ cm (2015). The y-axis shows the frequency for each level of uncertainty. The total area under each line is normalized to 1.

corrections which correct the β-beating and the normalized dispersion simultaneously [1].

During the 2016 winter shutdown the reason of the movement was traced to cryogenics pressure and temperature regulation and an adequate stabilization system was introduced [20]. These kind of orbit drifts were not observed in 2016.

C. 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 [21]. In this article we define the positive waist shift in the direction of the focusing magnet for that plane. Since the two beams travel in opposite direction the direction of positive waist shift will be in opposite physical direction for the two beams in the same plan. This is shown graphically in Fig. 4. The measured β^* and the waist offset measured using K-modulation are shown in Table I. We clearly observe a systematic offset of the waist in the direction of the focusing quadrupole and about 10% β-beating. This was unexpected

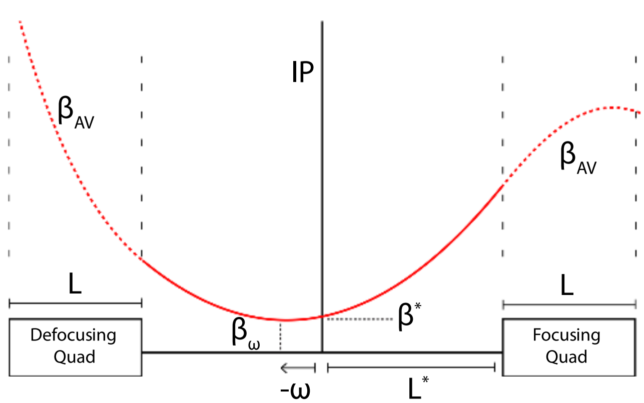

FIG. 4. The conceptual layout and nomenclature for the parameters close to the IP. The read line represents the β-function. The figure is taken from [26].

TABLE I. The measured β^* and waist shift after the final corrections for the 2015 run.

IP	Beam	β_x^* [cm]	β_y^* [cm]	w_x [cm]	w_y [cm]
1	1	88 ± 1	86 ± 1	25 ± 2	23 ± 1
1	2	82 ± 1	83 ± 1	18 ± 2	21 ± 1
5	1	86 ± 1	86 ± 5	22 ± 2	24 ± 9
5	2	87 ± 1	83 ± 2	24 ± 2	16 ± 5

since the estimates of the magnetic errors were unlikely to create such an offset. The assumptions of the gradient uncertainties were based on WISE [22,23], which provides smaller uncertainty values than presented in [24]. 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 [25], which showed that it was less than 4% chance that the errors are following a normal distribution with 0.11% [24] 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. It is possible to propagate the measured β-functions at the BPMs to the IP assuming good knowledge of the model and the size of the imperfections. It was simulated that if quadrupole gradient errors are below 0.04%, as expected in [22], it would result in an accurate estimate of the β^* from the TbT measurement. 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 too small to explain the discrepancy.

III. 2016 COMMISSIONING

As described in the previous sections there were several factors limiting optics correction in 2015. In 2016 a regulation of the cryostat was implemented which mitigated the rapid orbit drifts [20]. The problem with the systematic β-function waist offset led to the integration of K-modulation data in optics calculations. K-modulation [5,27] for LHC optics correction 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 magnets. The β-functions which are 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 the waist shift [28]. After this experience, the tool for K-modulation measurements was fully automated to obtain the result on-line [26,29], which then could be used in the corrections. The details of this improved procedure and corrections are described in the following sections.

A. Improvements in K-modulation measurements

The K-modulation method has been used to measure the β-functions at the IPs. 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 [26,27,30]. The optics functions are then interpolated towards the IP, thus providing measurements of β^* and the waist.

The online implementation of the K-modulation tool allows for a faster and more accurate measurement of the β^*. Figure 5 shows a typical modulation applied to the quadrupole right of IP1 and the resulting modulated horizontal and vertical tunes in beam 2. The frequency and amplitude of the modulation is generally limited by the quadrupole power converters and the speed of the tune measurement.

K-modulation measurements are performed 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 ($Q_x = 64.31$, $Q_y = 59.32$).

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 6 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 efficiently clean the data and 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 (2.5×10^{-5}) and the standard deviation resulting from the binning of the base-band-tune (BBQ) [31] 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. 6. The typical uncertainty of the fit is between 0.6 m^2 and 1 m^2. The main variation of the error bar coming from the fit is the quality of the tune measurement.

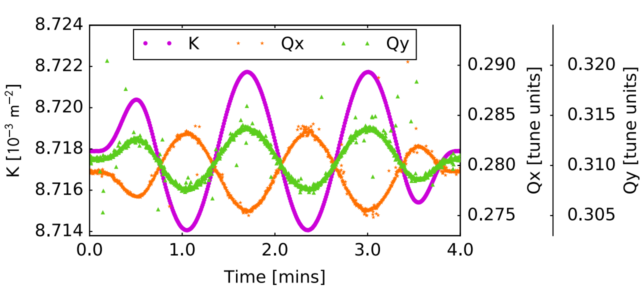

FIG. 5. Horizontal and vertical tune measurements of beam 2 during the gradient modulation of the first quadrupole right of IP1.

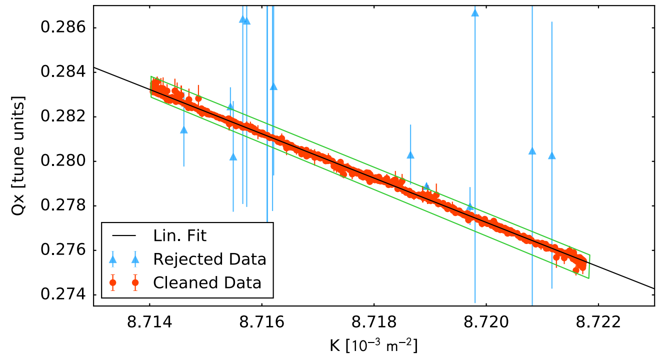

FIG. 6. Linear fit of horizontal tune data for beam 2 with an illustration of the data cleaning process. The rejected data is shown in blue. An online tool is used to specify the domain of acceptance shown in green.

B. Local corrections

Local corrections are applied around the IPs where the magnets are individually powered [1]. 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 was 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 calculation of the local corrections. The upper plot in Fig. 7 shows how corrections calculated in 2015 and 2016 both correct the phase beating. However, in the lower plot of Fig. 7 we observe that it is only the 2016 correction that is able to fit the β-function measured at the two most inner magnets. This illustrates why only the corrections applied in 2016 were able to compensate the waist shift.

In Table II the local corrections for 2012, 2015, and 2016 are shown. The optics errors changed during LS1 which

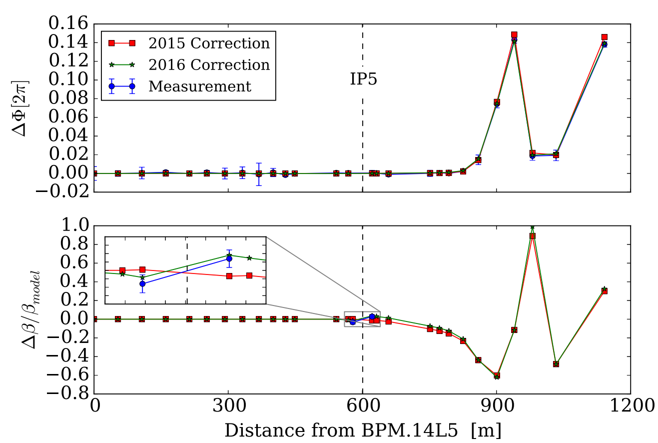

FIG. 7. A comparison between how the 2016 and 2015 corrections would correct the phase error (on top) and the local β-beating (bottom). The red line shows the 2015 correction, the green 2016 and the blue show the measurement. Note that both the lines and points show the deviation from the ideal model.

TABLE II. Local correction strengths from 2012, 2015, and 2016 for (IR) quadrupoles. The circuits of the final focusing quadrupoles are highlighted with a bold font. The powering of the triplets has been $|K_0| = 0.008730\ \mathrm{m}^{-2}$ throughout the years. The polarity indicates if K_0 is positive or negative using the LHC Software Architecture (LSA) convention.

		Δk (10^{-5} m^{-2})			
	Circuit	2012	2015	2016	Polarity LSA
IR1	**ktqx1.l1**			1.23	−
	ktqx1.r1	1.0		−1.23	+
	ktqx2.l1	1.0	0.35	0.65	+
	ktqx2.r1	−1.4	−0.7	−1.0	−
	ktqx3.l1			1.22	−
	ktqx3.r1			−1.22	+
	kq9.l1b1	1.5			−
IR5	**ktqx1.l5**		2.0	2.0	−
	ktqx1.r5		−2.0	−2.0	+
	ktqx2.l5	0.7	1.9	0.27	+
	ktqx2.r5	1.05	1.9	1.48	−
	ktqx3.l5			1.49	−
	ktqx3.r5			−1.49	+
	kq4.l5b2	3.80			−

lead to the need for different corrections. This was initially believed to be due to the higher energy, but during a special run at 2.51 TeV in 2015 it was measured that the errors were consistent at the two energies [32]. The sources of the difference between 2012 and 2015 remain unknown, but could derive from longitudinal misalignments or aging of the magnets. The difference in the corrections between 2015 and 2016 derive from the before mentioned correction of the waist shift.

Corrections were also calculated using the Action Phase Jumps method [33,34]. The suggested corrections from this method were similar to the 2015 corrections [35].

In the case of well calibrated BPMs it is possible to reconstruct the β-functions from the amplitude of the oscillations [36,37]. The initial strategy 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. While the method was not accurate enough to constrain the corrections, it provided important information for debugging the new K-modulation software.

C. Global corrections

Application of the local corrections reduced the β-beating to a peak of about 20%. To reach a lower β-beating a global correction approach is needed. This is required since not all the errors are originating from the IRs. The better corrected optics also provides more margin for other effects such as beam-beam and reduces the luminosity imbalance between the experiments. Global correction in the LHC is

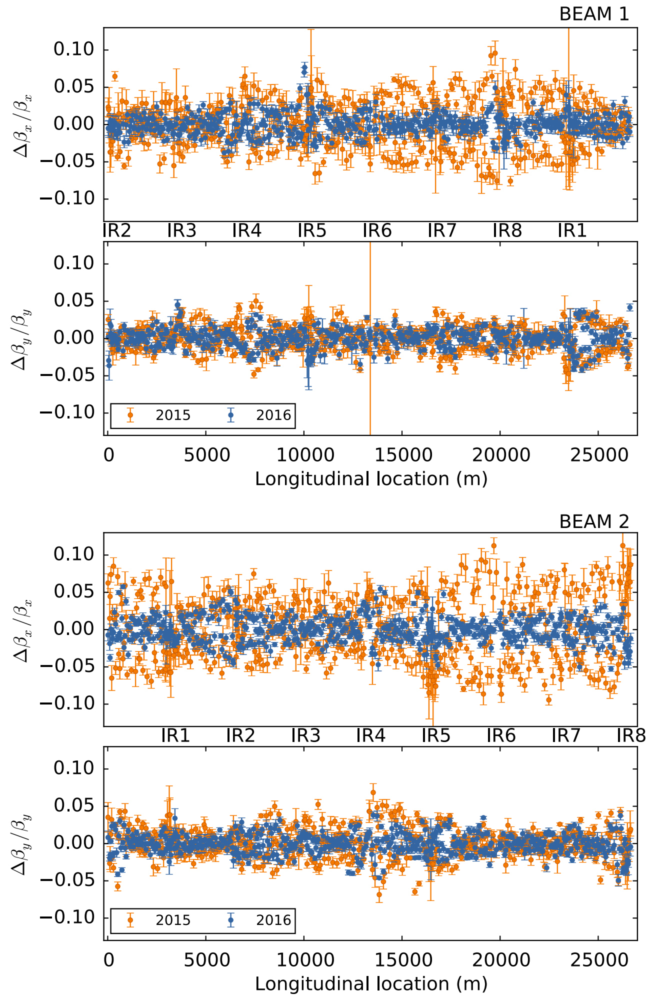

FIG. 8. β-beating at 40 cm β^* for beam 1 (upper) and beam 2 (lower) plot.

based on a response matrix approach. The correction method was improved in 2016 by taking the measurement uncertainties into account as weights. Additionally the quantity specific weights can be specified, i.e., giving a higher weight

TABLE III. Normalized dispersion and min, max and rms of the β-beating (in %) in 2015 and 2016.

		2015			2016		
	Beam	Min	Max	rms	Min	Max	rms
$\frac{\Delta D_x}{\sqrt{\beta_x}}[\sqrt{m}]$	1	−2.2	2.5	0.78	−1.7	1.9	0.52
$\frac{\Delta D_x}{\sqrt{\beta_x}}[\sqrt{m}]$	2	−3.1	2.5	1.13	−1.8	1.6	0.62
$\frac{\Delta\beta_x}{\beta}$	1	−7.6	9.6	3.18	−3.8	7.7	1.42
$\frac{\Delta\beta_y}{\beta}$	1	−4.8	5.0	1.69	−4.2	4.5	1.35
$\frac{\Delta\beta_x}{\beta}$	2	−9.5	11.3	4.24	−5.3	5.8	1.79
$\frac{\Delta\beta_y}{\beta}$	2	−6.8	6.8	2.07	−4.9	3.8	1.42

TABLE IV. The measured β^* before correction, after local correction and after global corrections for the $\beta^* = 40$ cm optics.

	IP 1 β^* [cm]				IP 5 β^* [cm]			
	Beam 1		Beam 2		Beam 1		Beam 2	
	H	V	H	V	H	V	H	V
Before Corr	62.3 ± 1.2	73.1 ± 1.0	41.7 ± 1.3	75.4 ± 3.0	48.0 ± 0.8	30.9 ± 0.1	45.8 ± 0.2	45.0 ± 0.8
After Local	41.2 ± 0.3	40.9 ± 0.1	36.6 ± 0.1	40.4 ± 0.4	35.7 ± 0.2	40.9 ± 0.2	40.4 ± 0.3	40.4 ± 0.1
After Global	39.8 ± 0.5	40.1 ± 0.1	39.8 ± 0.1	40.1 ± 0.1	39.9 ± 0.2	40.1 ± 0.1	39.5 ± 0.1	39.6 ± 0.2

to the β-functions close to the IP than to the phase advance. In every column, the response matrix contains gradients of weighted observables for a change in the model of a quadrupole strength as shown in Eq. (1). The division of two vectors is defined as a vector containing the division of the components with the same index. Quadrupole strength correction, which minimizes the parameters of interest, is obtained through the pseudoinverted response matrix and the measurement vector as shown in Eq. (2). By including 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.

$$\vec{R_i} = \left(\frac{\sqrt{w_{\phi_{x,y}}} \cdot \frac{d\overrightarrow{\phi_{x,y}}}{dk_i}}{\overrightarrow{\sigma_{\phi_{x,y}}}}, \frac{\sqrt{w_{\beta_{x,y}}} \cdot \frac{d\overrightarrow{\beta_{x,y}}}{dk_i}}{\overrightarrow{\sigma_{\beta_{x,y}}}}, \frac{\sqrt{w_{ND_x}} \cdot \frac{d\overrightarrow{ND_x}}{dk_i}}{\overrightarrow{\sigma_{ND_x}}}, \frac{\sqrt{w_Q} \cdot \frac{dQ_{x,y}}{dk_i}}{\sigma_{Q_{x,y}}} \right)^T \tag{1}$$

$$\Delta\vec{k} = -\mathbf{R}^{-1} \cdot \left(\sqrt{w_{\phi_{x,y}}} \left(\frac{\overrightarrow{\Delta\phi_{x,y}}}{\overrightarrow{\sigma_{\phi_{x,y}}}} \right), \sqrt{w_{\beta_{x,y}}} \left(\frac{\overrightarrow{\Delta\beta_{x,y}}}{\overrightarrow{\sigma_{\beta_{x,y}}}} \right), \sqrt{w_{ND_x}} \left(\frac{\overrightarrow{\Delta ND_x}}{\overrightarrow{\sigma_{ND_x}}} \right), \sqrt{w_Q} \frac{\Delta Q_{x,y}}{\sigma_{Q_{x,y}}} \right)^T \tag{2}$$

where, $\Delta\vec{k}$ is a vector with the change of k-values, $\mathbf{R}$ is the response matrix composed of the column vectors $\vec{R_i}$ $w_{\beta_{x,y}}$, $w_{\phi_{x,y}}$, $w_{Q_{x,y}}$ w_{ND_x}, are the quantity specific weights, $\vec{\phi}$ is a vector containing the phase advances, $\vec{\beta}$ is a vector with the β-functions close to the IPs, $\vec{ND_x} = \frac{\vec{D_x}}{\sqrt{\beta_x}}$ is a vector with the normalized dispersion, $Q_{x,y}$ are the tunes, and $\vec{\sigma}$ are the vectors of the uncertainties of the measurements.

IV. RESULTS

After application of local and global corrections, a final set of measurements with the AC dipole and K-modulation were performed. As a result of the previously mentioned improvements an unprecedented rms β-beating below 2% was achieved in 2016. Figure 8 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 [38,39]. A small number of BPMs were also removed due to incorrect synchronization of the TbT data. The peak and rms values of the β-beating measured using K-modulation are detailed in Table III. More important than the reduction of the overall β-beating is the improved control at the IP1 and IP5. Table IV shows the measured β^* before and after the different corrections. The final rms β-beating at the IPs is below 1% resulting in an expected luminosity imbalance below 1%. The larger uncertainty in the measurement of the β^* for horizontal beam 1 at IP1 derives from a poor tune measurement. Figure 9 shows a comparison of the average shift of the β^* waist. Table V shows the well corrected waist after the global correction with a maximum deviation of 5.5 cm.

Correction of normalized dispersion was seen to have improved significantly since the problem of orbit drifts were corrected before the 2016 commissioning. The improvements are detailed in Fig. 10 and Table III.

V. BEYOND 2016

The β^* in 2017 is planned to be between 0.33 m and 0.4 m [14]. This will bring the LHC into a regime where the

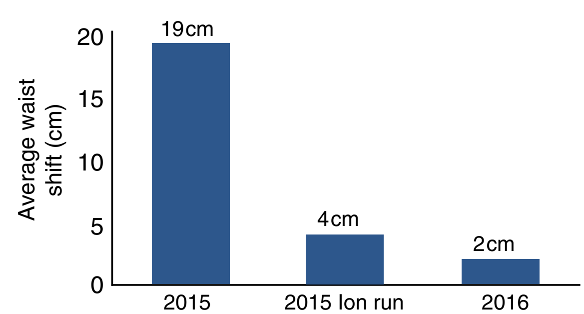

FIG. 9. The average shift of the waist of the β-function at IP1 and IP5 for the $\beta^* = 40$ cm optics.

TABLE V. Measured values of waist offset in IP1 and IP5 after global corrections.

IP	Beam	w_x [cm]	w_y [cm]
1	1	-5.5 ± 1.6	2.3 ± 0.9
1	2	1.7 ± 0.7	0.1 ± 1.1
5	1	3.2 ± 0.9	0.5 ± 0.7
5	2	4.2 ± 0.5	-3.6 ± 1.1

instantaneous luminosity will be limited by the experiments. For a luminosity above 2×10^{34} cm^{-2} s^{-1} pile up in the experiments will be too severe and some type of luminosity leveling will be required [40]. The other limitation on instantaneous luminosity comes from cryogenic power [41]. It is estimated that it can sustain a maximum luminosity of 1.75×10^{34} cm^{-2} s^{-1}. While the experiments and the cryostats are not able to cope with too high luminosity the physics program is still interested in maximizing the integrated luminosity. This triggered the idea of having a luminosity leveling using a larger β^* at the beginning of the fill and then decreasing it [42]. In that way the luminosity would stay rather constant throughout the fill. This forces additional constraints on the optics corrections, which would have to be valid for a range of optics. In order to investigate how well the corrections work at different configurations both measurements and simulations were performed. The results are summarized in Fig. 11. It is clearly visible in simulations that a change of β^* of a factor 2 also increases the rms β-beating by about a factor 2. The same trend is observed for the measurements. This demonstrates that the global corrections are working very well for a certain configuration, but are unable to correct effectively a different optics configuration. In order

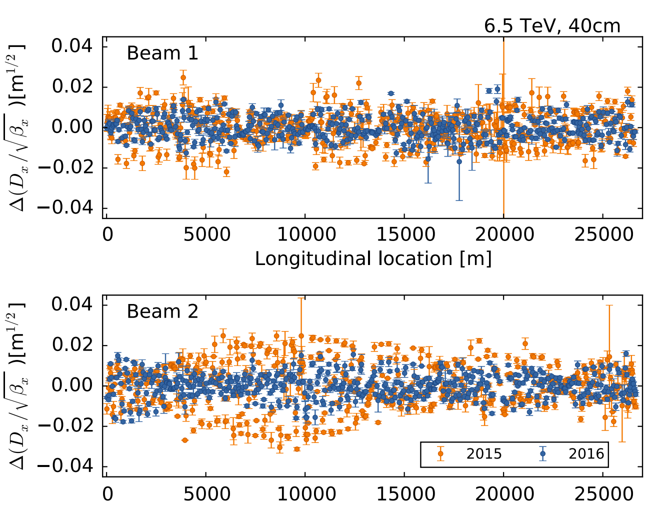

FIG. 10. Comparison of dispersion beating at β^* of 40 cm between 2015 and 2016.

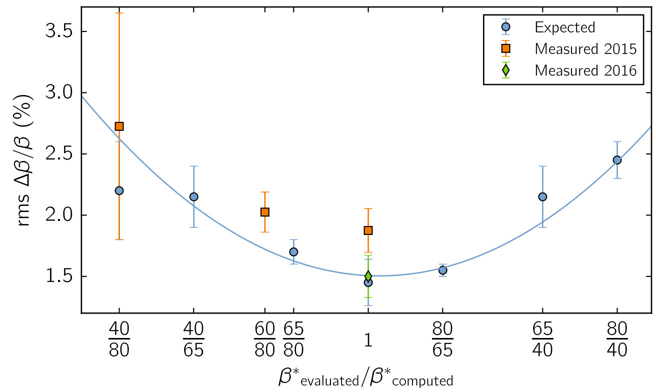

FIG. 11. The rms β-beating when calculating a correction at a certain β^* and applying it at a different. The blue points are based on simulations while the green and orange are based on measurements.

to have a good global corrections for all configurations the errors for all magnets would need to be known, including how they scale with the powering of the magnets. This is currently under investigation and the goal is to identify the errors of the individual magnets. It would also be possible to correct at several different β^* in steps of about 25%.

VI. CONCLUSIONS

The LHC optics has been successfully commissioned down to a 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 optical configuration so far. Even so an unprecedented β-beating in a high energy proton collider has been achieved. In particular a control below 1% has been demonstrated for the β^*. This is of importance to provide equal luminosity to the two main experiments. The well-corrected waist is also of importance to provide as much aperture as possible while keeping the β^* at the minimum. These results have only been possible due to the recent improvement in obtaining β-functions on-line from the K-modulation, the incorporation of these 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.

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