

# OPTICS MODEL

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## Abstract

The LHC optics quality after the 2015 commissioning is reviewed. Optics corrections were limited due to a variety of problems. This includes disturbed dispersion measurements due to orbit drifts and an unexpected shift of the IP  $\beta$ -function ( $\beta^*$ ) waist. The resulting issues will become more critical at the smaller  $\beta^*$  of 40 cm foreseen for 2016. Therefore, an improved optics correction strategy with desired actions for the 2016 commissioning is proposed. The optics quality during combined ramp and squeeze is presented and the benefits of ballistic optics measurements are discussed. The optics stability over time and the correction of interaction region (IR) non-linearities are also reviewed.

## INTRODUCTION

The first LHC optics commissioning at an energy of 6.5 TeV was preceded by many efforts in understanding the LHC optics and improving the necessary tools for achieving the highest precision of optics measurements and corrections [1–10]. In this scope, two reviews had been organized, the first in 2011 and a second one during the first long shutdown (LS1) in 2013 [11–13]. 2015 was the first optics commissioning that benefited from using the  $N$ -BPM method [14] for an increased precision of the measurement of  $\beta$ -functions. Further improvements are the increased AC dipole excitation plateau and BPM recording time, that together allow to take turn-by-turn optics measurements for up to 6600 turns, which is a factor of 3 increase compared to 2012.

## OPTICS QUALITY

Optics measurements before corrections showed a peak  $\beta$ -beat of more than 100%. Local corrections of the strongest quadrupole error sources in the interaction regions (IRs) reduced the  $\beta$ -beat to below 15%. Global corrections reduced the  $\beta$ -beat further to below 11%, cf. Fig. 1. For the first time constant global corrections for a range of  $\beta^*$  from 80 cm to 40 cm have been derived, which is a more time efficient approach. For beam 2 the used global corrections were only optimized for a  $\beta^*$  between 80 cm and 65 cm, and a separate correction for  $\beta^* = 40$  cm could have an even better performance. However, since the corrections which were optimized for larger  $\beta^*$  reduce the  $\beta$ -beat well enough also for  $\beta^* = 40$  cm, and due to time efficiency considerations, it was decided to use the same correction from 80 cm to 40 cm also for beam 2.

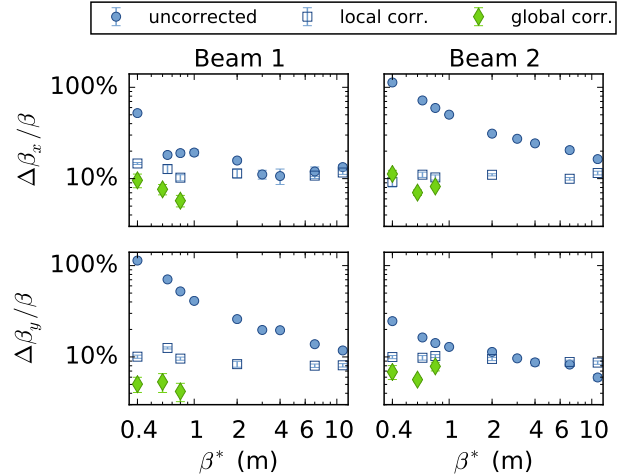


Figure 1: Peak  $\beta$ -beat for different  $\beta^*$  at the ATLAS and CMS interaction point before corrections, and after local and global corrections.

## Combined ramp and squeeze

The combined ramp and squeeze (CRS) is a technique that allows faster turnaround times of the LHC operational cycle, by starting to reduce the  $\beta^*$  during the energy ramp up instead of after top energy has been reached [15, 16]. During an MD of a CRS to 3 m [17, 18], optics measurements have been performed at several intermediate points during the energy ramp up, cf. Figs. 2 and 3.

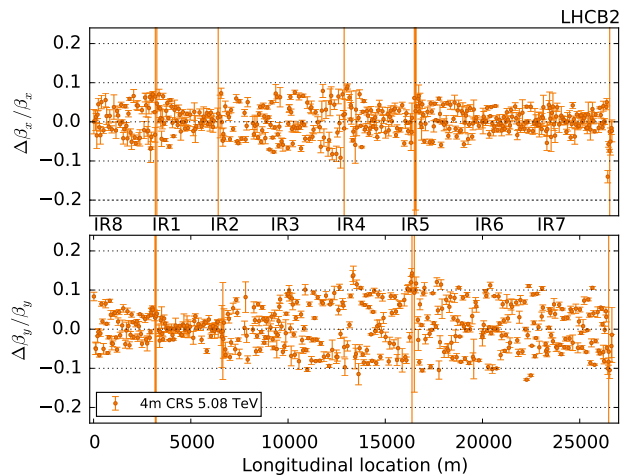


Figure 2:  $\beta$ -beat measurements during the energy ramp up of a CRS at an energy of 5.08 TeV and a  $\beta^*$  of 4 m for beam 2

These measurements are difficult to coordinate since the energy ramp up can not be paused at certain points. The

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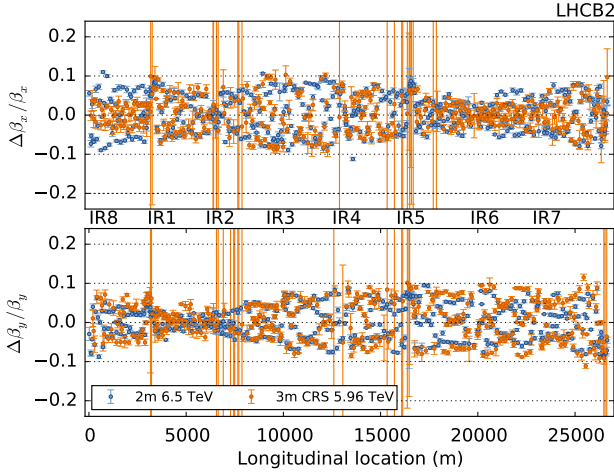


Figure 3:  $\beta$ -beat measurements during the energy ramp up of a CRS at an energy of 5.96 TeV and a  $\beta^*$  of 3 m for beam 2. A comparison is shown to a static measurement at 6.5 TeV and a  $\beta^*$  of 2 m.

measurements were taken close to the matched points of the CRS and repeated during a second ramp. Although the precision of the measurement is lower compared to a static measurement, due to fewer acquired turns and fewer repetitions of the measurement, the agreement to measurements at 6.5 TeV is very good. The optics quality is no limit for a CRS even to smaller  $\beta^*$ .

### Optics stability

In this section the stability of the LHC optics on different time scales is discussed. For injection optics many measurements exist that indicate a good reproducibility after time periods of up to 6 months. For squeezed optics however not enough measurement of the same optics under same conditions exist to make a statement. Figure 4 shows two measurements at a  $\beta^*$  of 40 cm which are separated by 4 months. The agreement is good, however the second measurement was performed with a small oscillation amplitude and fewer repetitions which resulted in large error bars.

On an even larger time scale, one can compare the local corrections which were used for the triplet magnets in 2012 and 2015, cf. Table 1. The local corrections deviate significantly also when comparing the effect on the betatron phase, cf. Fig. 5.

This indicates that the 2012 corrections could not be re-used after 3 years. Possible reasons for the discrepancy are (i) the different energy (4 TeV to 6.5 TeV), (ii) effects from the long technical stop, (iii) new misalignments and (iv) magnet ageing. A counterargument to the energy difference as the source of the discrepancy is the fact that the optics errors that were observed in measurements at 2.51 TeV in 2015 were compatible with the ones at 6.5 TeV.

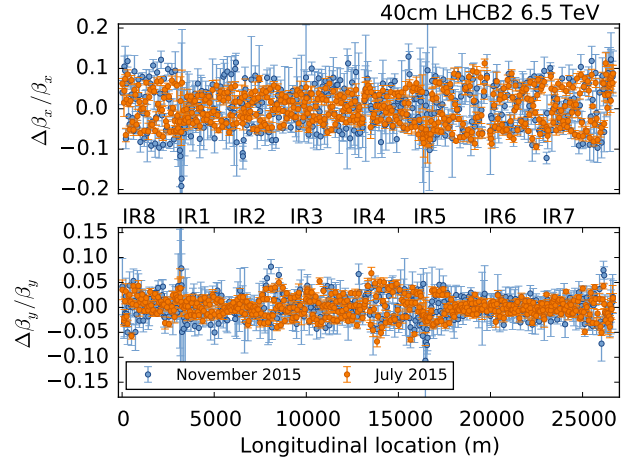


Figure 4: Comparison of the measured  $\beta$ -beat for a  $\beta^*$  of 40 cm of two measurements which are separated by 4 months.

Table 1: Local correction of triplet magnets in IR1 and IR5 from 2012 in comparison to 2015.

Region	Circuit	$\Delta k$ ( $10^{-5}m^{-2}$ )		
		2012	2015 protons	2015 ions
IP1	MQXA.1R1	1.00		-1.23
	MQXA.1L1			1.23
	MQXB.2L1	1.00	0.35	0.65
	MQXB.2R1	-1.40	-0.70	1.00
	MQXA.3L1			1.22
	MQXA.3R1			-1.22
IP5	MQXA.1L5		2.00	2.00
	MQXA.1R5		-2.00	-2.00
	MQXB.2L5	0.70	-0.09	2.00
	MQXB.2R5	1.05	1.90	1.60
	MQXA.3L5			1.50
	MQXA.3R5			-1.50

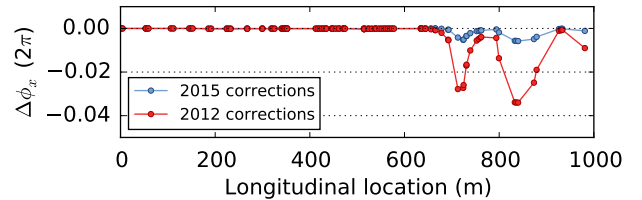


Figure 5: Resulting deviations of the betatron phase for local corrections in IR1 of beam 1 which were used in 2012 and 2015.

## INTERACTION POINT OPTICS

Despite the globally very well corrected optics, an average discrepancy of 5% was observed in the interaction point  $\beta$ -function measured with k-modulation, cf. Table 2, which came along with an average shift of the  $\beta$ -function waist of

22 cm, cf. Table 3. An accurate analysis of the k-modulation measurements was only done at the end of the proton run, so that no correction of this effect was possible during the commissioning [19, 20]. Furthermore, the gradient errors of the triplet magnets that could cause such a waist shift are 4 times larger than the assumed gradient uncertainties. The assumptions of the gradient uncertainties were based on WISE [21, 22], which provides smaller uncertainty values than [23]. Both references however do not fully explain the observed errors in the triplet magnets. Therefore, neither was this deviation of the  $\beta$ -function waist expected, nor were turn-by-turn measurements sensitive enough to detect it.

Corrections of the  $\beta^*$  waist shift were calculated and successfully tested with protons during the optics commissioning for the ion run [24]. The corrections are for 3 quadrupoles as large as 0.23 %, cf. Table 1. The resulting waist shift after corrections is shown in Table 4.

Table 2:  $\beta^*$  for the 80 cm optics from k-modulation measurements.

		$\beta^*$ (cm)	
		horizontal	vertical
Beam 1	IP1	$87.8 \pm 1.3$	$86.5 \pm 0.7$
	IP5	$86.2 \pm 1.1$	$86 \pm 5$
Beam 2	IP1	$81.9 \pm 1.3$	$82.7 \pm 0.6$
	IP5	$86.7 \pm 1.4$	$83 \pm 2$

Table 3: Waist shift of the  $\beta^*$  for the 80 cm optics for the proton run from k-modulation measurements. A positive value indicates a shift towards the focusing quadrupole in the corresponding plane.

		$\omega$ (cm)	
		horizontal	vertical
Beam 1	IP1	$24 \pm 1$	$23 \pm 1$
	IP5	$20 \pm 1$	$15 \pm 1$
Beam 2	IP1	$17 \pm 2$	$21 \pm 1$
	IP5	$22 \pm 1$	$11 \pm 1$

Table 4: Waist shift of the  $\beta^*$  for the 80 cm optics for the ion run from k-modulation measurements. A positive value indicates a shift towards the focusing quadrupole in the corresponding plane.

		$\omega$ (cm)	
		horizontal	vertical
Beam 1	IP1	$2 \pm 4$	$5 \pm 2$
	IP5	$-4 \pm 5$	$1 \pm 2$
Beam 2	IP1	$4 \pm 3$	$-4 \pm 2$
	IP5	$2 \pm 4$	$-9 \pm 3$

Simulation show that the corrections that were tested for the ion run at a  $\beta^*$  of 80 cm, will not work for the proton optics at a  $\beta^*$  of 40 cm, cf. Fig. 6. This means that new corrections need to be derived which aim to correct the phase and the waist shift simultaneously.

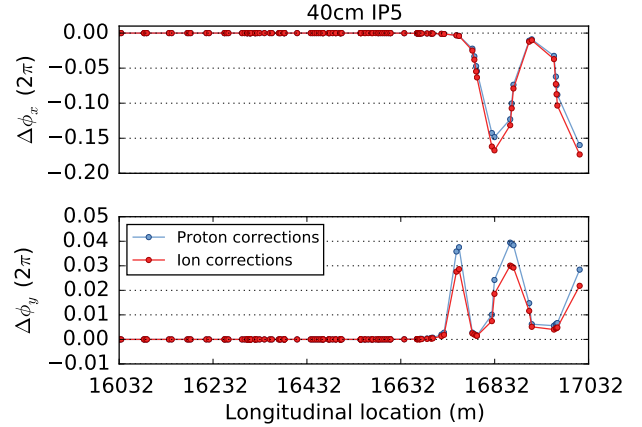


Figure 6: Resulting deviation of the betatron phase for local corrections in IR5.

## DISPERSION MEASUREMENTS

Quadrupole movements in IR8 [25], which resulted in orbit drifts, have disturbed many dispersion measurements. This limited global corrections, since the betatron phase and dispersion are corrected together. In Figure 7 the measured normalized dispersion is shown before and after global corrections. The very large error bars are a direct effect of the orbit drifts. Moreover, the values of the normalized dispersion before and after correction are very similar, which shows that the correction performance was limited. To mitigate this problem future off-momentum measurements should take place in periods where the IR8 triplet is moving only slowly.

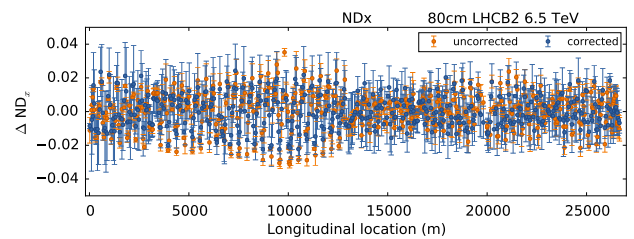


Figure 7: Normalized dispersion before and after global corrections for  $\beta^* = 80$  cm.

## OUTLOOK TO 2016

In the following paragraphs proposals for an improved strategy for future optics commissionings will be made, which mitigates the problems that were observed in 2015.

## Ballistic optics

Ballistic optics is a special optics where the triplet magnets in IR1 and IR5 are switched off. It has been tested during an MD in 2015 at injection energy for beam 2 [26]. It is a very useful study for local corrections as it allows to disentangle optics errors coming from triplet magnets and other IR magnets. Furthermore, it is necessary for the calibration of near-IP BPMs, which would facilitate the calculation of  $\beta$ -functions from the amplitude information of the BPM turn-by-turn data [27]. This has the potential to derive precise  $\beta^*$  from turn-by-turn optics measurements. For a complete set of data, further measurements are needed in 2016 for both beams and at 6.5 TeV. The analysis of these measurements will be beneficial for later optics measurements, and should therefore take place at the beginning of the commissioning.

## K-modulation

To identify possible  $\beta^*$  waist shifts, precise optics measurements are required close to the IP, which is currently only possible with k-modulation measurements. The proposed optics correction strategy, cf. Fig. 8, includes k-modulation measurements already before and after local corrections. This will allow to identify possible waist shifts and include their correction in the computation of local corrections. This requires furthermore upgrades on the k-modulation tools, as the measurement needs to be (i) robust, (ii) IP driven with (iii) online results and (iv) a direct import into the optics correction tools.

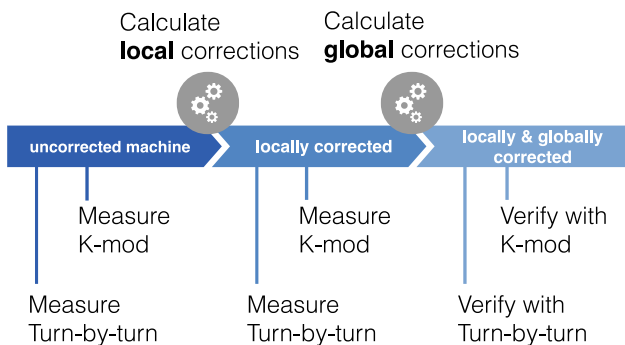


Figure 8: Schematic of the proposed improved optics measurement and correction strategy, which includes k-modulation measurements in the calculation and verification of local corrections.

## Non-linear IR errors

Corrections of non-linear errors in the IR were proposed for 2016 as they aim to increase the dynamic aperture, which would result in a longer beam lifetime and ultimately into more integrated luminosity. At RHIC corrections using 10- and 12-pole correctors increased the integrated luminosity by 4 % [28]. Corrections for several multipole errors have been studied at the LHC in the past and are ready for testing (IR2:  $b_3$ ; IR1:  $b_3, b_4, a_4$ ; IR5:  $b_4$ ) [29]. Further multipole errors need to be studied as they are either not completely

understood (IR1:  $a_3$ ; IR5:  $b_3$ ) or have not been studied yet (IR5:  $a_3, a_4$ ).

## ACKNOWLEDGMENT

We are extremely thankful to E. Calvo Giraldo, S. Faroukh, M. Gasior, M. Giovannozzi, P. Hagen, L. Jensen, V. Kain, M. Kuhn, M. Lamont, N. Magnin, S. Redaelli, B. Salvachua, E. Todesco and all the operation crew for invaluable support and fruitful discussions.

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