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LHC optics commissioning at $\beta^* = 40\,\mathrm{cm}$ and $60\,\mathrm{cm}$

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Summary

This paper reports on the results of the $\beta^* = 40\,\mathrm{cm}$ and $\beta^* = 60\,\mathrm{cm}$ optics commissioning for the LHC at 6.5 TeV from MD blocks I and II.

Contents

1 Introduction

The optics commissioning of the $\beta^* = 40\,\mathrm{cm}$ optics was part of the first machine development block of the LHC in run II. The measurements were performed on 22.07.2015. The goal was to assess the quality of the optics after local and global corrections. The fill number was 4033 and the beam process SQUEEZE-6.5TeV-80cm-40cm-v3-2015_V1@494_[END]. KSS magnets were turned off, and all MCS magnets were still in operation. All measurements were performed using the AC dipole system to excite oscillations of the beams [1]. Measurements with only local optics corrections have been performed on 17.05.2015 and serve as a reference in comparisons. The effect of optics measurements on the beam size is investigated in Section 2, as in past measurement an increase of the transverse beam size was observed after AC dipole excitations [2]. The setting of the collimators during the $\beta^* = 40\,\mathrm{cm}$ measurements is shown in Section 3. In Section 4 the resulting β-beating after local and global corrections is shown. The measured coupling is shown in Section 5. In Section 6 we present observations from off-momentum measurements. This includes dispersion, the chromatic β-beating and non-linear chromaticity. Furthermore, another set of measurements was performed with larger oscillation amplitudes in each plane separately. This allowed to observe detuning with amplitude, which is discussed in Section 7. A short measurement of the $\beta^* = 60\,\mathrm{cm}$ optics was performed during MD block II on 30.08.2015, and the results are shown in Section 8.

2 Beam size stability

During the LHC optics commissioning in 2015, several times an increase of the transverse beam size was observed after exciting the beam [2]. Problems of the AC dipole with an increased excitation plateau of 6600 turns [3], compared to 2200 turns in 2012, was suspected as a possible reason. Although a fault correction of the AC dipole has been done prior to the MD, as a precaution, during this MD most measurements were performed with only 2200 turns, except for the last measurements after 13:50 where 6600 turns were used. In Fig. 1 the evolution of the beam size during the optics measurements is shown. Up to 12:15 on-momentum measurements were performed. In Beam 2 a slow increase of the beam size can be observed in both planes. From 12:50 to 13:20 off-momentum measurements were taken. An increase of the vertical beam size can be seen for the last off-momentum excitation for Beam 1 at around 13:20. From 13:25 to 13:50, measurements with large excitation in each plane were performed. The beam size was stable except for the last two excitations of Beam 1 vertically. From 13:50 measurements with 6600 turns were performed. For Beam 1 the first three measurements do not seem to increase the beam size significantly. For the last three measurements of Beam 1 and also for all four measurements of Beam 2 small beam losses occurred. The situation is much better than in [2] and there is currently no problem with longer AC dipole excitation.

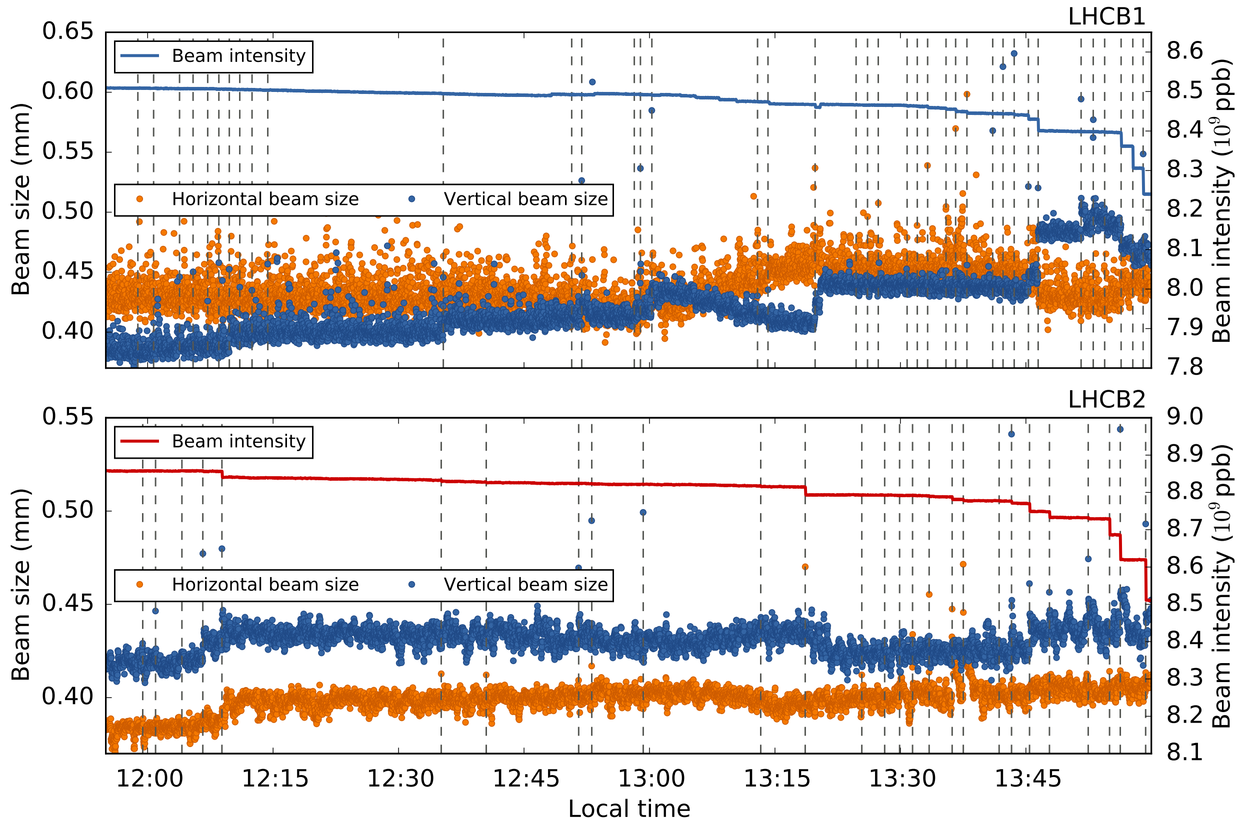

Figure 1: Beam size measurements from synchrotron radiation monitors during the measurements. The times of an AC dipole excitation to the beams are indicated with dashed gray lines. Beam intensity measured with beam current transformers (BCTs) is shown as well.

3 Collimator settings

The ramp was done with nominal collimator settings. Before the orbit of the beam was flattened, the collimators were moved out. The tertiary collimators in IR2 and IR8 were symmetrized by moving the jaw closer to the center to the same absolute value as the other one. The collimators in IR3, IR7 and IR6 were also opened to leave more margin for the measurements. The final collimator settings at top energy and $\beta^* = 40\,\mathrm{cm}$ is shown in Table 1. The TCTP horizontal collimator in IR1 for Beam 1 was set to $\pm 18\,\mathrm{mm}$, the other horizontal collimators were set to $\pm 13.5\,\mathrm{mm}$. The vertical tertiary collimators in IR1 and IR5 were set to $\pm 8.6\,\mathrm{mm}$.

Table 1: Collimator settings at top energy and $\beta^* = 40\,\mathrm{cm}$.

	Collimator Family	Collimator Settings
IR7	TCP/TCSG/TCLA	12σ / 13σ / 14σ
IR3	TCP/TCSG/TCLA	20σ / 20σ / 20σ
IR6	TCSP/TCDQ	12σ / $\pm 15\,\mathrm{mm}$
IR1	TCTPH_B1	$\pm 18\,\mathrm{mm}$
IR1	TCTPH_B2/TCTPV	$\pm 13.5\,\mathrm{mm}$ / $\pm 8.6\,\mathrm{mm}$
IR5	TCTPH/TCTPV	$\pm 13.5\,\mathrm{mm}$ / $\pm 8.6\,\mathrm{mm}$
IR2	TCTPH/TCTPV	Symmetrized from squeeze 10 m
IR8	TCTPH/TCTPV	Symmetrized from squeeze 3 m

4 Optics correction

Optics measurements have been performed with local and global corrections. The global corrections were calculated from optics measurements at a β^* of 80 cm, 65 cm and 40 cm, and aimed to correct phase advances and dispersion with the following two separate knobs per beam:

- 2015_Global_Beam1_80-40cm_disp
- 2015_Global_Beam1_80-40cm_phase
- 2015_Global_Beam2_80-65cm_disp
- 2015_Global_Beam2_80-65cm_phase

For Beam 1 a common correction was derived for β^* from 80 cm to 40 cm. For Beam 2 the correction was initially derived for β^* from 80 cm to 65 cm, as a separate correction for $\beta^* = 40\,\mathrm{cm}$ could have an even better performance. Due to efficiency considerations, it was decided to use the same corrections also for the $\beta^* = 40\,\mathrm{cm}$ optics, as they were expected to correct also this optics well enough. In case of unexpected discrepancies a second iteration could have been calculated and tested during the MD. Figures 2 and 3 show the resulting β-beating measurements. The RMS and peak β-beating is shown in Table 2. Since the corrections worked as expected, with a peak β-beating of 11% (5-7% in vertical planes), no further corrections were calculated. The interaction point (IP) β-functions (β^*) are shown in Table 3, with a maximum deviation of 7 %.

Table 2: RMS and peak β-beating after local and global corrections at $\beta^* = 0.4\,\mathrm{m}$.

		Beam 1		**Beam 2**	
		x	**y**	**x**	**y**
$\frac{\Delta\beta}{\beta}(\%)$	peak	9.6 ± 1.6	5.0 ± 1.0	11.2 ± 1.1	6.8 ± 1.2
	rms	3.2	1.7	4.0	2.0

Table 3: Measured β^*-values ($\beta^* = 40\,\mathrm{cm}$), with a maximum deviation of 7 %.

LHCB1	β_x (m)	β_y (m)
IP1	0.41 ± 0.02	0.42 ± 0.02
IP2	10.3 ± 0.5	10.1 ± 0.2
IP5	0.41 ± 0.04	0.390 ± 0.014
IP8	2.9 ± 0.2	2.97 ± 0.04
LHCB2	**β_x (m)**	**β_y (m)**
IP1	0.41 ± 0.04	0.40 ± 0.04
IP2	9.9 ± 0.2	10.0 ± 0.4
IP5	0.43 ± 0.03	0.395 ± 0.008
IP8	2.78 ± 0.14	3.05 ± 0.08

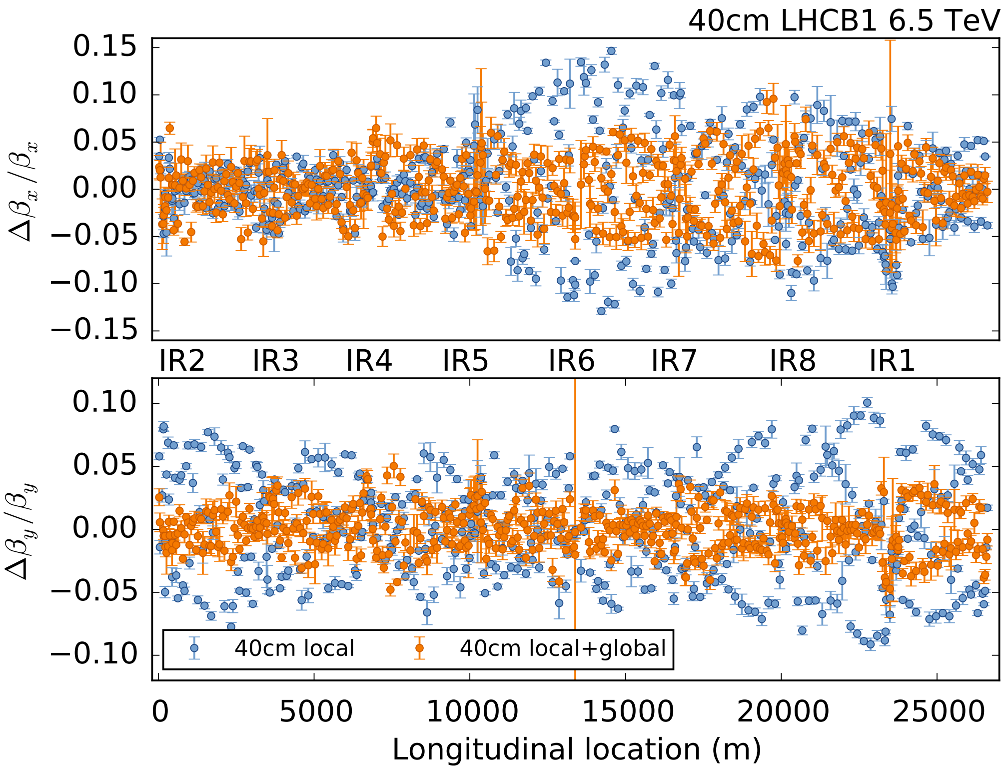

Figure 2: β-beating for Beam 1.

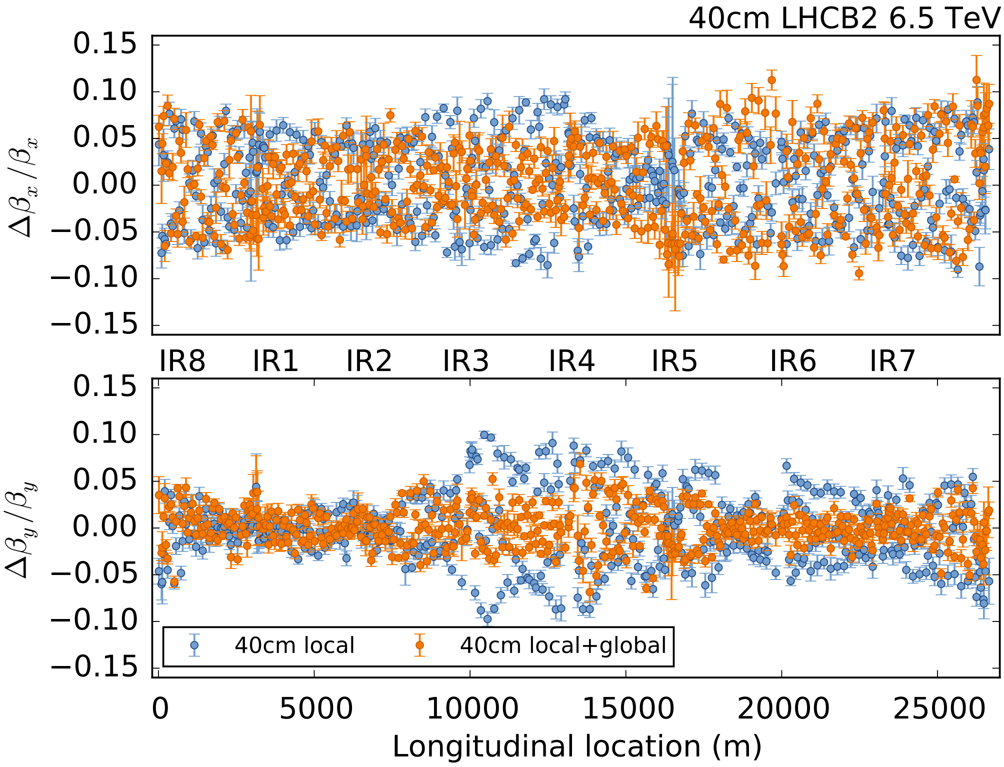

Figure 3: β-beating for Beam 2.

5 Coupling

The results of coupling measurements are shown in Figs. 4 and 5 for $\beta^* = 40\,\mathrm{cm}$ and in comparison for $\beta^* = 60\,\mathrm{cm}$. The coupling was in both cases well corrected. A small jump can be seen for both beams at IP1, which is more pronounced for $\beta^* = 40\,\mathrm{cm}$, and for Beam 1 at $\beta^* = 60\,\mathrm{cm}$ seems to go in the opposite direction. The reason for this might be a general shift of the phase of about 90°, cf. Fig. 6. These observations point to an uncorrected error in IP1. A further insight is required to understand why this error could not be corrected yet.

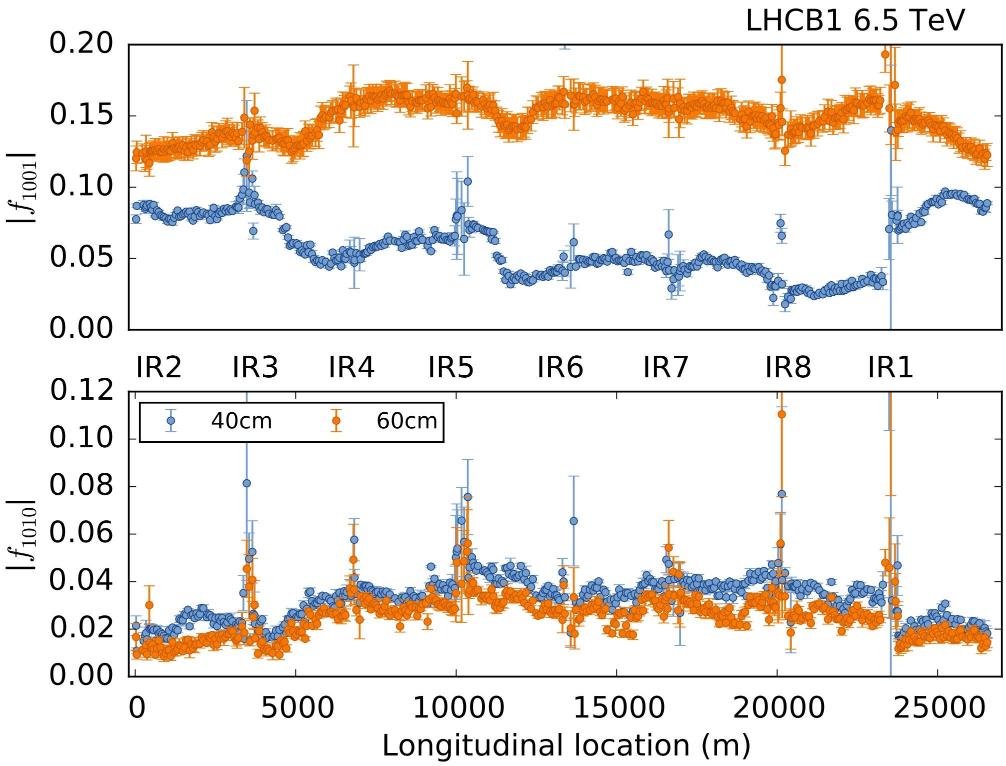

Figure 4: Coupling for Beam 1.

The chromatic coupling was measured for the two beams. The method to reconstruct the chromatic coupling requires that the tune split remains rather constant during the measurement. This was not the case due to mainly non-linear chromaticity, and because of that we can not present an accurate value of the chromatic coupling. The two problems with a tune shifts are:

1. The f_{1001} is strongly dependent on the fractional tune split $(Q_x - Q_y)$.
2. The reconstruction of the f_{1001} itself is also dependent on the fractional tune split, which is fixed in the present algorithm.

A more complete explanation of the issue with this method and suggestions to overcome the problems are reported in [4].

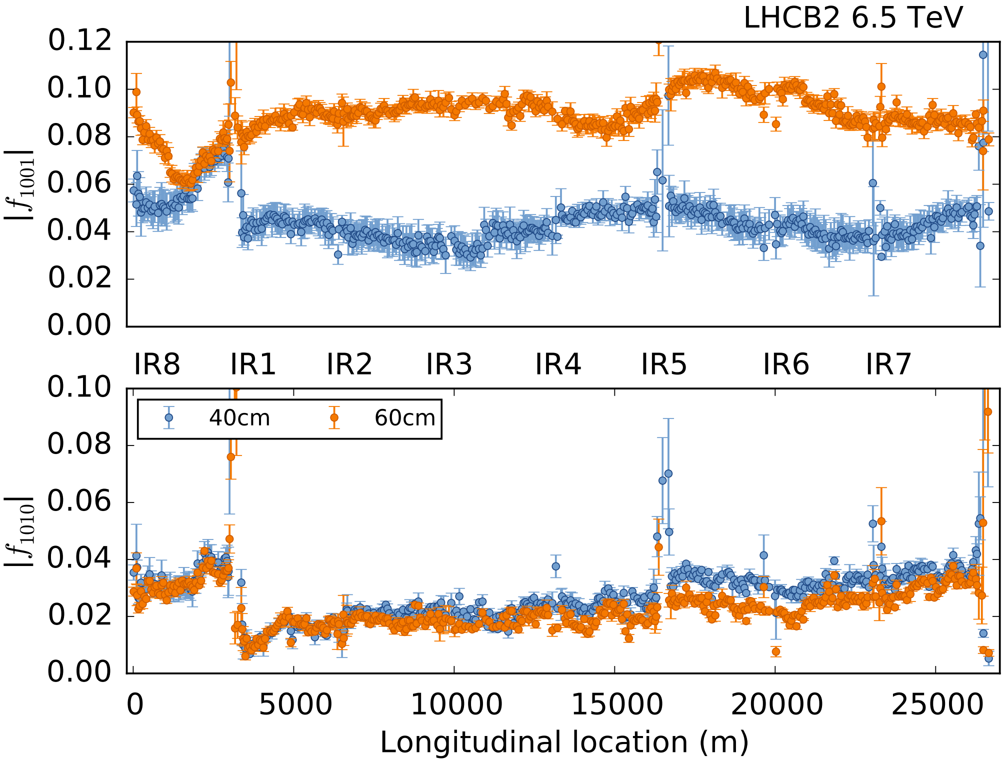

Figure 5: Coupling for Beam 2.

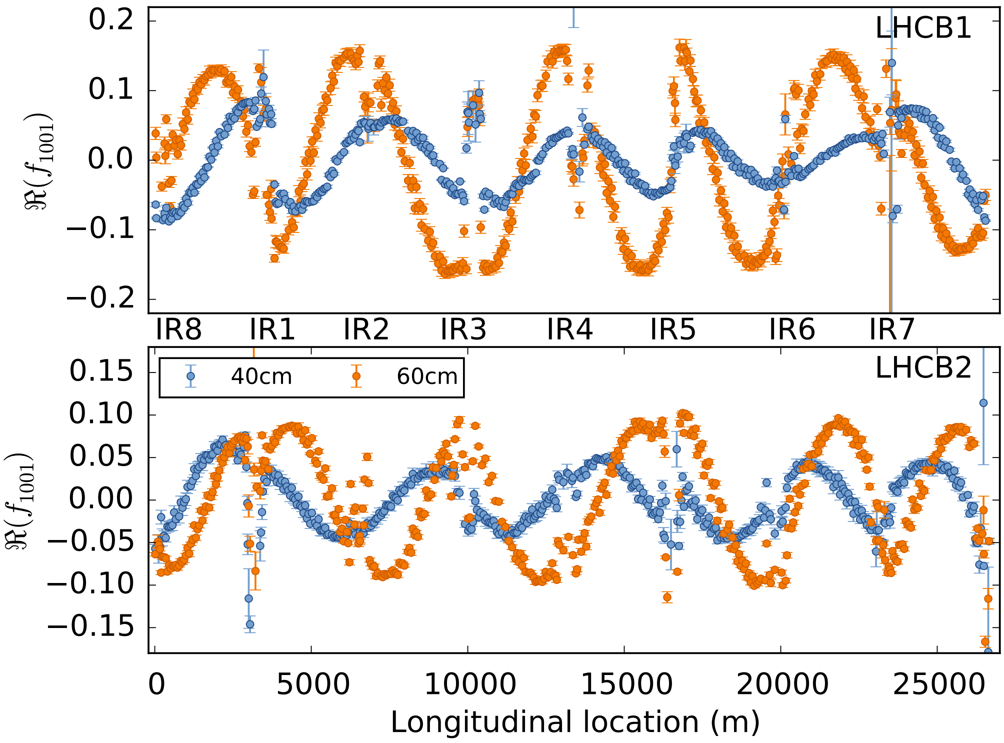

Figure 6: Real part of the f_{1001} for both beams.

6 Off-momentum measurements

Off-momentum measurements were performed at four different points with an rf frequency change of ±40 Hz and ±80Hz, which corresponds to a $\Delta p/p_0$ of $\pm 3.2 \cdot 10^{-4}$ and $\pm 6.4 \cdot 10^{-4}$. Tune change during off-momentum measurements is shown for both beams in Fig. 7. The simulations suggest that the model is overestimating the non-linear errors of the machine.

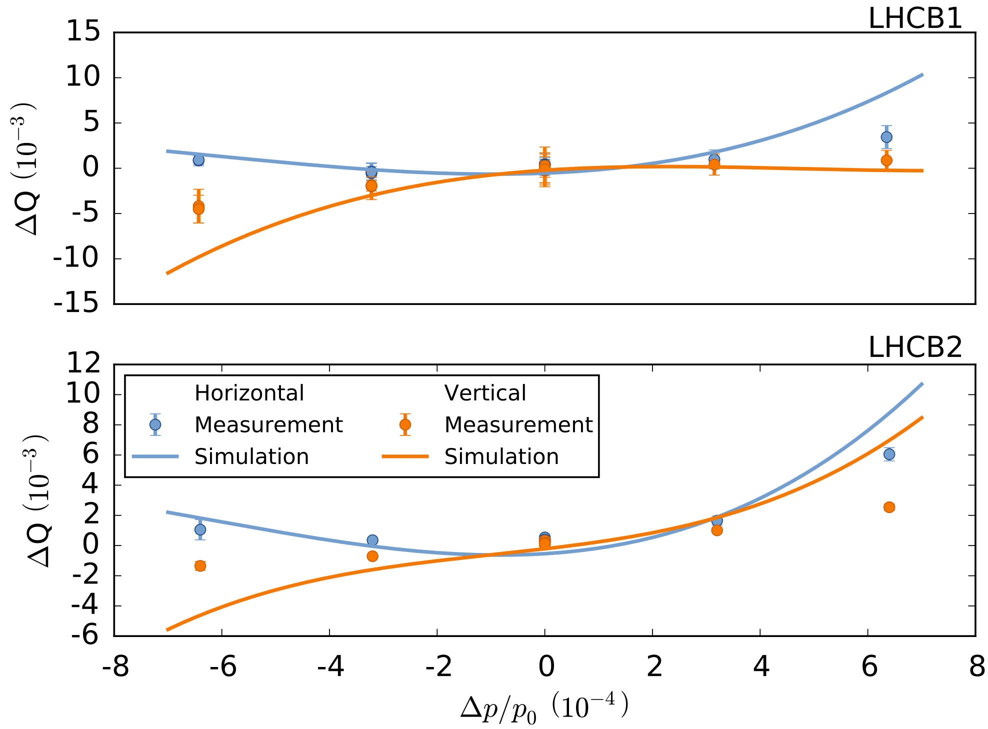

Figure 7: Tune evolution during off-momentum measurements.

6.1 Dispersion

During the MD, large uncertainties of the measured dispersion were observed, which was already the case for a few measurements during the optics commissioning. Offline analysis revealed that the on-momentum closed orbit is not consistent with the off-momentum closed orbits. The absolute value of the orbit shift from on-momentum to +40 Hz is significantly deviating from the orbit shift to −40 Hz. However the absolute value of the orbit shift from +40 Hz to +80 Hz is very consistent with the orbit shift from −40 Hz to −80 Hz. The cause of this discrepancy, which is more pronounced for Beam 1, is not yet understood. Further measurements with smaller rf frequency changes have been done at a different day. This showed that for the closed orbit which is derived from the BPM turn-by-turn data at some point during the measurements a jump occurred and following measurements had a different offset of the closed orbit. Correcting this jump would in this case make all points consistent again. This issue, which is most likely related to the BPMs might have limited the performance of optics corrections in the past. As a temporary solution only consistent measurements should be analyzed together. For the $\beta^* = 40\,\text{cm}$ analysis, the on-momentum measurements were disregarded, as they were not consistent with all other measured closed orbits. Instead, the analysis was performed as if the +40 Hz measurement was on-momentum. The results are shown in Figs. 8 and 9, where a small reduction of the dispersion beating after the optics corrections is visible.

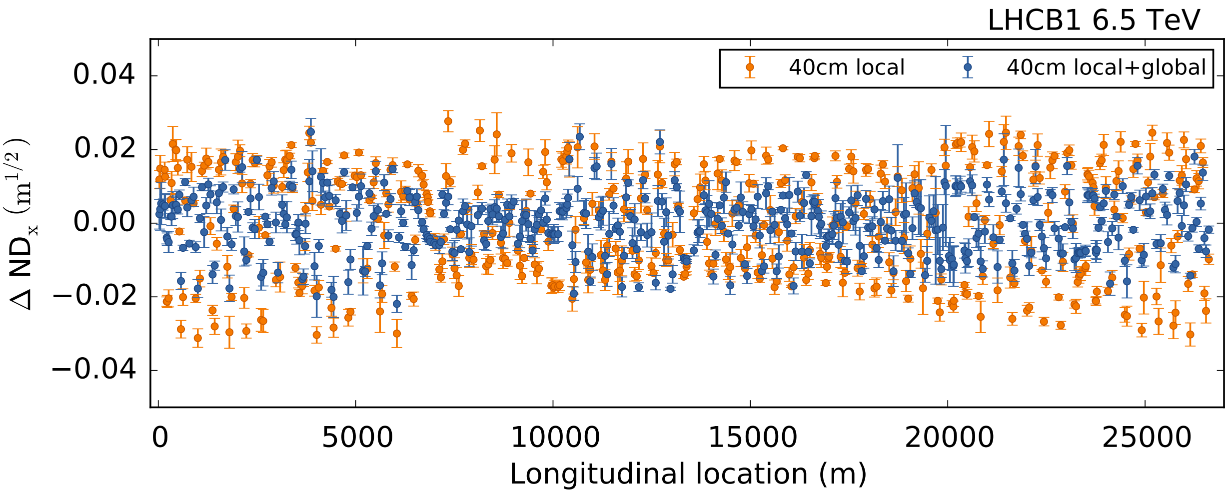

Figure 8: Normalized dispersion measurement for Beam 1.

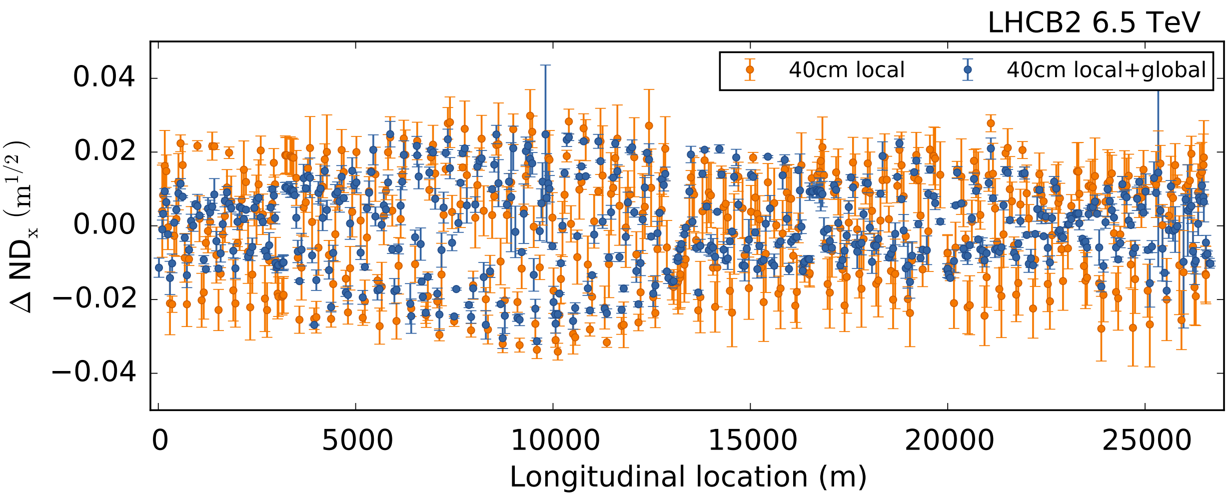

Figure 9: Normalized dispersion measurement for Beam 2.

6.2 Chromatic β-beat

Chromatic aberrations of the β-function after corrections are represented with the Montague function (W) [5]. It is invariant in achromatic regions, and therefore an indicator for chromatic imperfections. The measured W functions are shown in Figs. 10 and 11. A good agreement between the model and measurement confirms the good optics corrections. An example of the W functions before corrections can be found in [6].

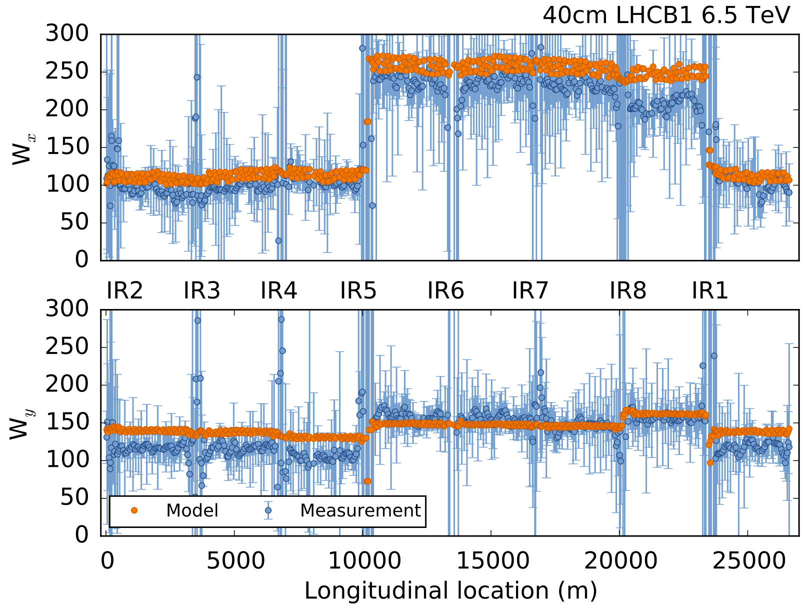

Figure 10: Montague function for Beam 1 after corrections.

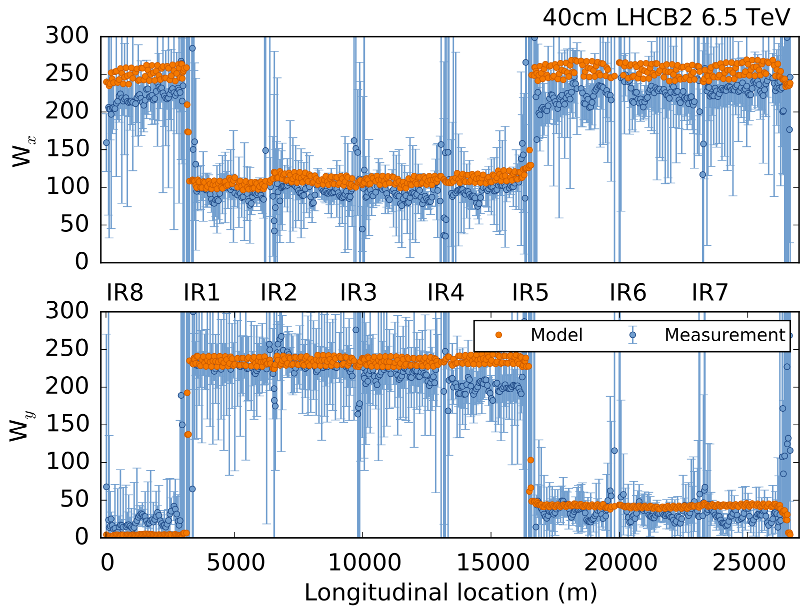

Figure 11: Montague function for Beam 2 after corrections.

7 Amplitude detuning

A method for calculating the amplitude detuning at high energy at the LHC with an AC dipole has been demonstrated in [7]. Measurements with large beam oscillation amplitudes up to 4σ of the nominal beam size ($\epsilon = 3.75\,\mu$m) have been performed during the MD. The observed amplitude detuning is shown in Figs. 12 and 13 together with the fit of a pure parabola. The fit results for the equation $\Delta Q = \Delta Q_0 + m \cdot A^2$, with the beam oscillation amplitude A in units of σ of the nominal beam size, are shown in Table 4. The simulated amplitude detuning uses a non-linear model of the LHC, where measured multipole errors from 3rd (sextupolar) to 11th order were applied. The settings during the measurement were used for the KCS, KCO and KCD corrector magnets, and tune and chromaticity was matched as well to the values of the measurement. A second simulation was done with a model where octupolar errors were corrected using the octupolar correctors at IP1 and IP5 (KCOX). The measured amplitude detuning is in between the model with and without corrections, which suggests that the triplet non-linearities are overestimated or a cancellation effect occurs which is absent in the model.

Table 4: Parabola fit of the measured amplitude detuning.

LHCB1	ΔQ_0 (10^{-4})	m (10^{-5})
Horizontal	3.3 ± 0.8	6.3 ± 1.0
Vertical	-1.8 ± 0.4	-2.0 ± 0.4
LHCB2	ΔQ_0 (10^{-4})	m (10^{-5})
Horizontal	1.2 ± 0.1	3.6 ± 0.1
Vertical	0.0 ± 0.8	-4.2 ± 1.4

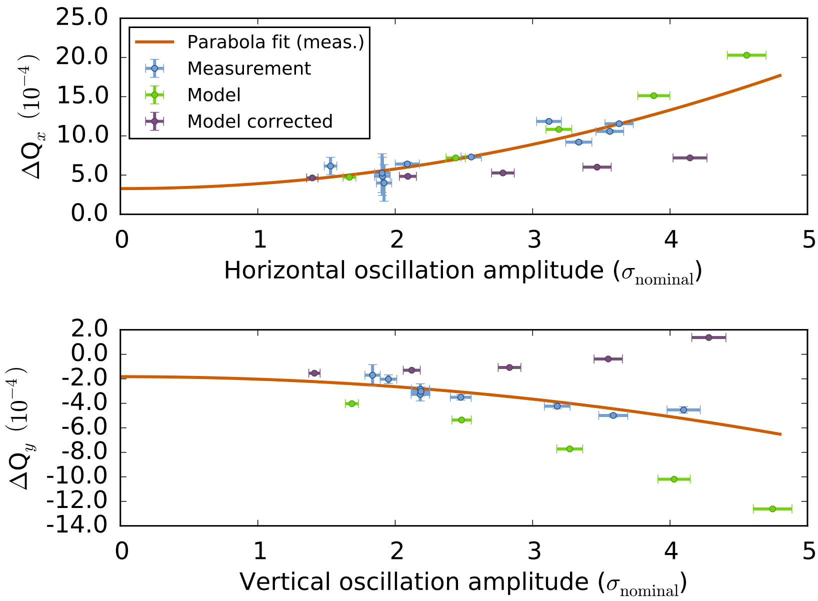

Figure 12: Amplitude detuning for Beam 1 excitations. The nominal beam size (σ_{nominal}) is based on an emittance of $3.75\,\mu$m.

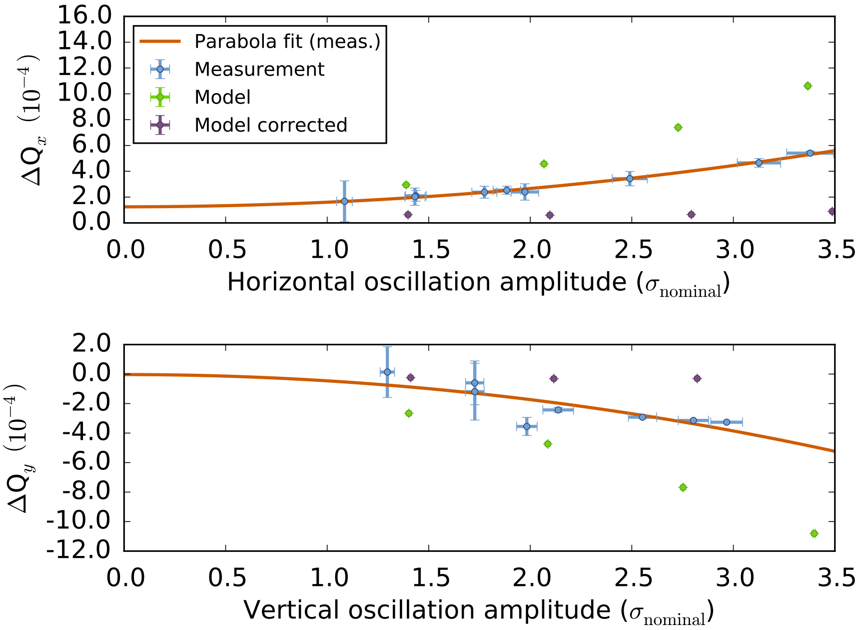

Figure 13: Amplitude detuning for Beam 2 excitations. The nominal beam size ($\sigma_{\mathrm{nominal}}$) is based on an emittance of $3.75\,\mu$m.

8 60cm optics measurements

The optics for $\beta^* = 60$ cm have been measured using the global corrections which are used for a β^* range from 80 cm to 40 cm, cf. Section 4. The resulting β-beating is shown in Figs. 14 and 15, and the measured dispersion beating in Figs. 16 and 17. The peak and rms β-beating is shown in Table 5, with a peak β-beating below 8 %. The measured β^* values are shown in Table 6 with a maximum deviation below 4 %. The dispersion measurement, which had the same problem as described in Section 6.1, shows a similar dispersion beating as the $\beta^* = 40$ cm measurements.

Table 5: RMS and peak β-beating after local and global corrections at $\beta^* = 0.6$ m.

		Beam 1		**Beam 2**	
		x	**y**	**x**	**y**
$\frac{\Delta\beta}{\beta}(\%)$	peak	7.6 ± 1.0	5.3 ± 1.2	7.0 ± 0.5	5.6 ± 0.3
	rms	2.3	2.0	1.9	1.9

Table 6: Measured β^*-values ($\beta^* = 60$ cm), with a maximum deviation below 4 %.

	LHCB1		LHCB2	
	β_x (m)	β_y (m)	β_x (m)	β_y (m)
IP1	0.61 ± 0.03	0.604 ± 0.019	0.60 ± 0.03	0.592 ± 0.011
IP5	0.609 ± 0.018	0.58 ± 0.03	0.62 ± 0.04	0.60 ± 0.03

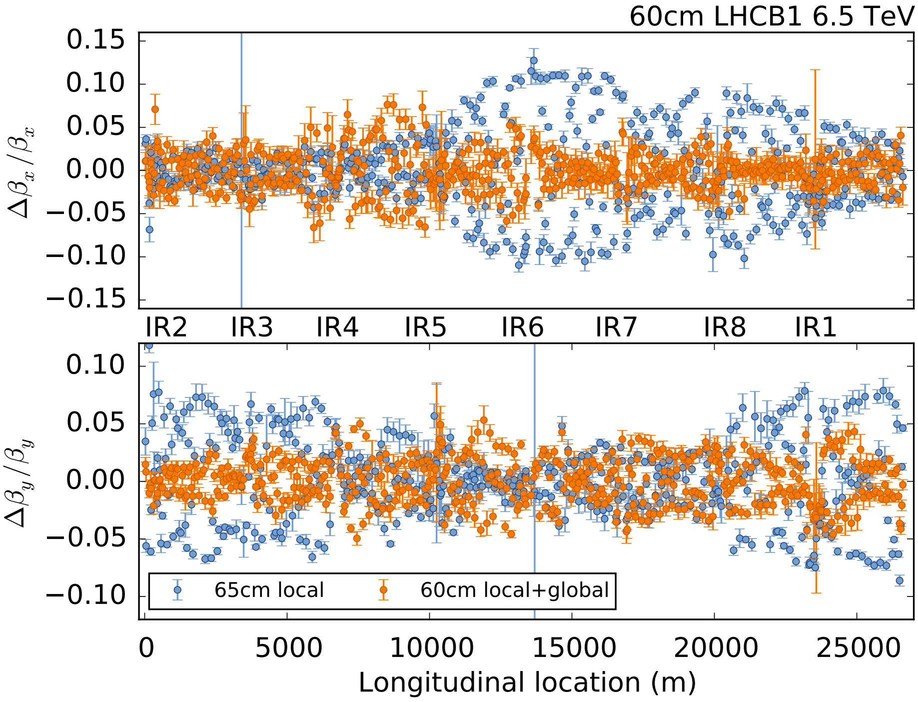

Figure 14: β-beating for Beam 1 at $\beta^* = 60\,\text{cm}$ after corrections compared to $\beta^* = 65\,\text{cm}$ before corrections.

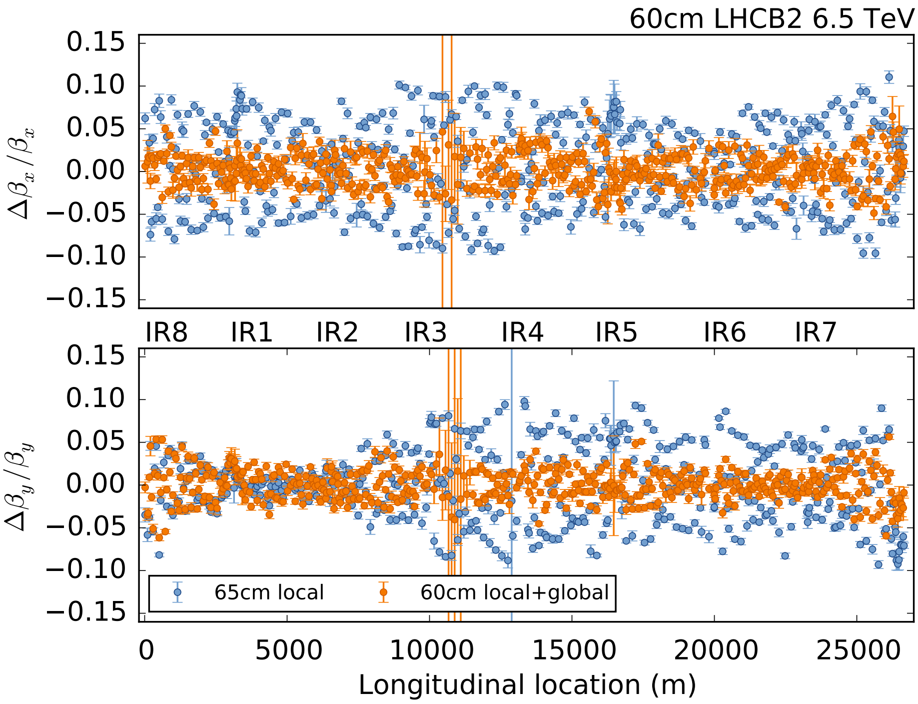

Figure 15: β-beating for Beam 2 at $\beta^* = 60\,\text{cm}$ after corrections compared to $\beta^* = 65\,\text{cm}$ before corrections.

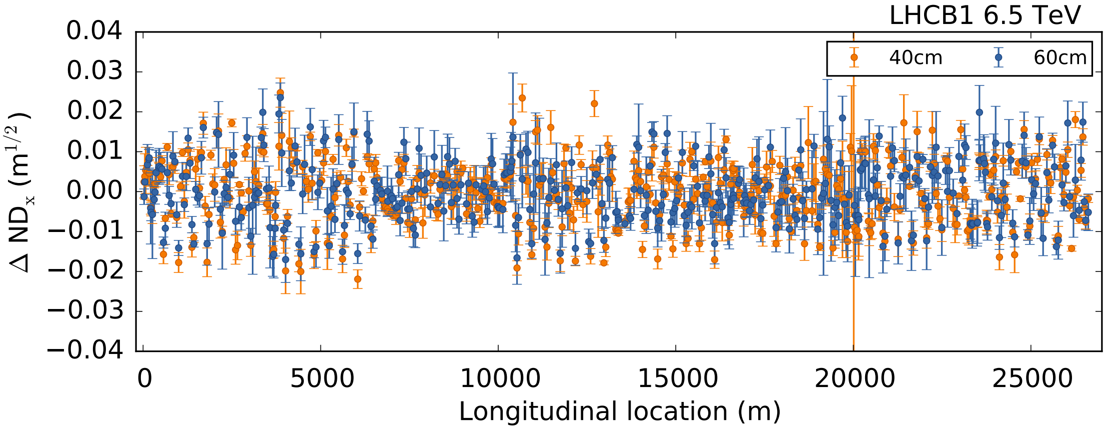

Figure 16: Normalized dispersion measurement for Beam 1 at a β^* of 40 cm and 60 cm, both after corrections.

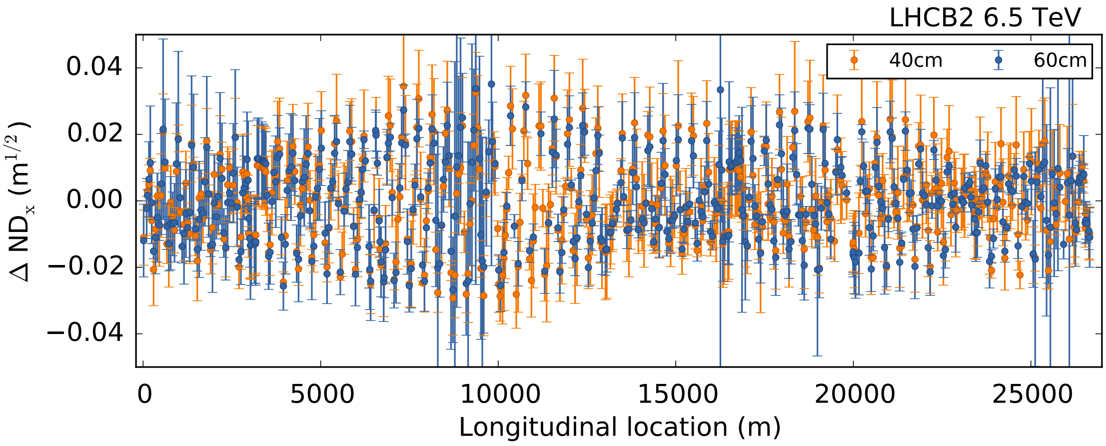

Figure 17: Normalized dispersion measurement for Beam 2 at a β^* of 40 cm and 60 cm, both after corrections.

9 Conclusions

Results of optics measurements for $\beta^* = 40$ cm after local and global corrections have been shown. For Beam 2 the used global corrections were only optimized for a β^* between 80 cm and 65 cm. However, also at $\beta^* = 40$ cm the β-beating is well corrected for both beams with a peak β-beating of 11% (5-7% in vertical planes). Off-momentum measurements show a slightly improved dispersion beating after corrections, but issues with the BPMs could have limited corrections. The good optics corrections is also verified by the measurement of chromatic β-beating. Furthermore, we have shown the measurement of non-linear chromaticity. Measurements with large beam oscillation amplitudes allowed to observe detuning with amplitude, which is smaller than the expectation from the model. Another measurement of the $\beta^* = 60$ cm optics has been presented as well, which also showed a very well corrected optics with a peak β-beating below 8 %.

Acknowledgments

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