**CERN-ACC-NOTE-2018-0051**

July 23, 2018
jcoellod@cern.ch

# MD2148: Flat optics

J. Coello de Portugal, S. Fartoukh, E. Fol, A. Garcia-Tabares, E. H. Maclean, L. Malina, T. Persson, P. K. Skowronski, M. Solfaroli, R. Tomas and A. Wegscheider

Keywords: optics, flat, measurements, corrections, ats

Summary

This note reports on the first attempt to measure and correct optics errors at $\beta^*$=60/30 cm and $\beta^*$=60/15 cm flat optics. In the absence of the Beam 2 vertical AC dipole, the ADT was used in AC-dipole mode to verify local corrections in IR1. A peak $\beta$-beating of 24% remained after global corrections in the horizontal plane of arc 45 of Beam 1. $\beta^*$ measurements with K-modulation showed a peak $\beta^*$-beating of 16% or larger, as IP1 measurement could not be completed. Global corrections for Beam 2 were also computed.

# Contents

# 1 Motivation and description

Flat optics are regarded as a backup scenario to reduce crossing angle and pile-up density in HL-LHC if the crab cavities are not operational [1, 2].

The target of this MD is to demonstrate the successful measurement and corrections of flat optics (Table 1) which is expected to be challenging as the $\beta$-functions reach up to 16 km in the triplets of IP1 and IP5 for $\beta^*$=60/15 cm. A $\beta$-beating on the 1% rms level has been demonstrated for nominal $\beta^*$=40cm round optics [3, 4, 5].

A broad timeline of this MD for Beam 1 is presented in Table 2.

| | |
|---|---|
| **Objective:** | Validate and correct flat optics down to 60/15 cm $\beta^*$. |
| **MD#:** | 2148 |
| **FILL#:** | 6445 |
| **Beam Process:** | MD → SQUEEZE-6.5TeV-ATS-65cm-60_15cm-2017_V1 |
| **Date:** | 01/12/2017 |
| **Start Time:** | 15:20 |
| **End Time:** | 21:00 |

Table 1: MD details.

| Time | Event ID | Description |
|---|---|---|
| 15:37:52 | 65_31_b1_beforeCouplCorr | Kick group with 3 kicks |
| - | Coupling correction | Table 3 |
| 15:48:41 | 65_31_b1_forCouplCorr2 | Kick group with 1 kicks |
| - | Second coupling correction | Trimmed Re $-3 \cdot 10^{-3}$ |
| 16:01:39 | 65_31_b1 | Kick group with 5 kicks |
| 16:40:39 | 60_15_b1 | Kick group with 1 kicks |
| - | Coupling correction | Table 4 |
| 18:19:26 | 65_31_b1_localIP1 | Empty kick group |
| 18:21:31 | 60_15_b1_after_couplingCorr | Kick group with 11 kicks |
| - | 2017_Local_flat_ATS | Table 5 |
| 18:23:09 | 65_31_b1_local_ip1 | Empty kick group |
| - | 2017_Coupling_Flat_ArcByArc_B1 | Arc-by-arc coupling correction |
| 19:22:22 | 60_15_b1_localIP1 | Kick group with 5 kicks |
| 19:23:27 | KMOD | Table 6 (IP1) |
| 19:26:01 | KMOD | Table 6 (IP5) |
| 19:33:14 | b1_flatoptics_60_15_measurement_for... | Kick group with 7 kicks |
| - | 2017_Global_Flat_wKmod_B1 | Global correction |
| 20:04:32 | b1_flatoptics_60_15_after_global_correction | Kick group with 7 kicks |
| 20:14:02 | b1_flatoptics_60_15_3Dkick | Kick group with 4 kicks |
| 20:51:30 | KMOD_AFTERCORR | Table 7 (IP5) |

Table 2: Measurements timeline for Beam 1. All the times relate to the end of each event.

## 2 $\beta^*$=60/30 cm measurements

Optics measurements began at $\beta^*_{x,y}$=60/30 cm.

A problem with the vertical AC-dipole in beam 2 was detected at the beginning of this MD, the experts were contacted but no fix was possible without an access to the tunnel. Therefore the MD continued with just the horizontal beam 2 AC-dipole. The measurements started after applying the coupling correction in Table 3, computed only with horizontal kicks for beam 2 [7].

| Knob | Trim [$10^{-3}$] |
|---|---|
| Beam 1 Real | -3 |
| Beam 1 Imag | 0 |
| Beam 2 Real | -3 |
| Beam 2 Imag | +5 |

Table 3: Coupling correction trimmed in at $\beta^*$=60/30 cm.

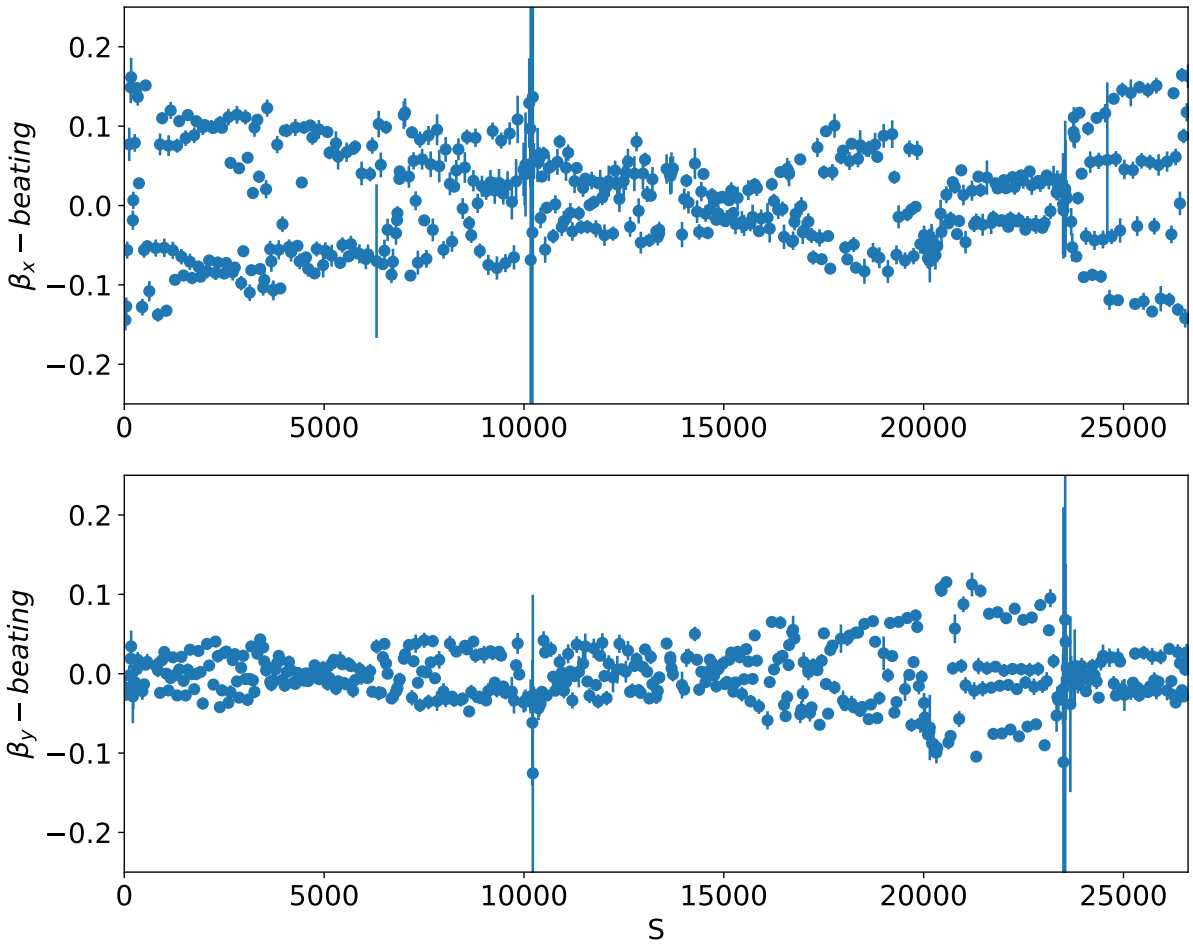


Figure 1: Beam 1 horizontal (top) and vertical (bottom) $\beta$-beating measurement at $\beta^*$=60/30 cm optics, showing a peak $\beta$-beating below 20% around the machine.

The optics measurement [8, 9] showed peak $\beta$-beating below 20%, see Figure 1, and thus it was decided to continue the squeeze to $\beta^*$=60/15 cm.

# 3 Measurements and corrections at $\beta^*$=60/15 cm

After few kicks for coupling corrections (see Table 4), the first optics measurements at $\beta^*$=60/15 cm showed a peak $\beta$-beating of around 30% in Beam 1, shown in Figure 3.

| Knob | Trim [$10^{-3}$] |
|---|---|
| Beam 1 Real | -2.5 |
| Beam 1 Imag | 1.4 |
| Beam 2 Real | 1.5 |
| Beam 2 Imag | 1.8 |

Table 4: Coupling correction trimmed in at 60/15 cm $\beta^*$.

Checking the IRs using the Segment-by-segment technique [10], a clear local error was found in IR1 in the vertical plane. It was analyzed using the automatic matching tool. The local correction is shown in Table 5 and ADT AC-dipole kicks were used to verify that the trim would not affect beam 2 optics dramatically. The ADT excitation is lower than the AC-dipole providing poorer measurements.

After applying the trim (with knob name: *2017_Local_flat_ATS*) the optics was measured again showing a reduction of about a factor 2 in the local phase deviation (Figure 2). The correction reduced vertical $\beta$-beating present in the machine by about 5%, see Figure 3.

| Corrector | Trim [$10^{-6}\mathrm{m}^{-2}$] |
|---|---|
| MQXB2.R1 | 0.4 |
| MQXA3.L1 | 1.1 |
| MQXA1.L1 | 1.1 |
| MQXB2.L1 | -1.1 |

Table 5: Local correction implemented in IR1. This values are the ones recorded in LSA.

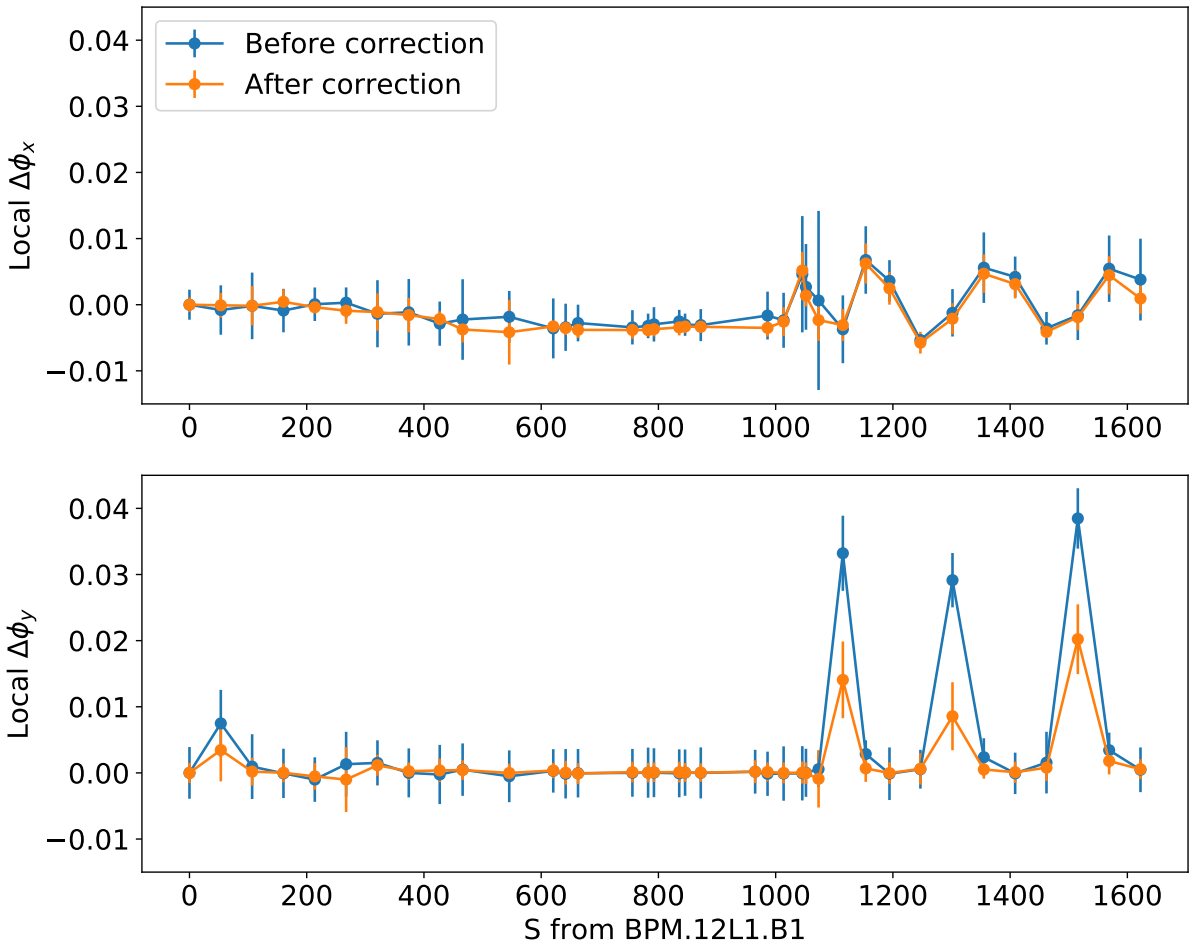


Figure 2: Local phase advance deviation from BPM.12L1.B1 in beam 1. A clear local error can be seen propagating from the triplets in the vertical plane. The local correction reduces the local phase beating by a factor 2.

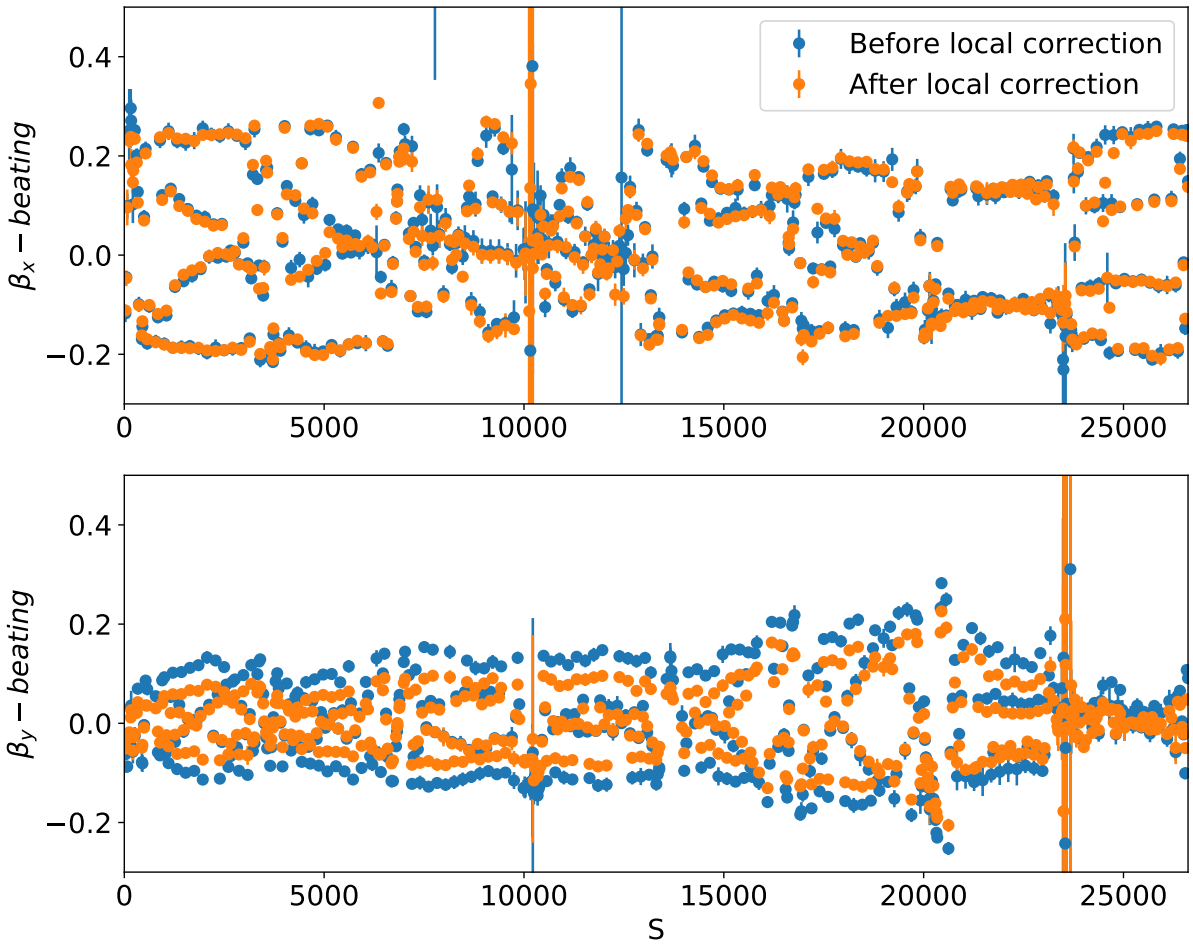


Figure 3: Effect of the local correction of IP1 of Beam 1 in $\beta$-beating, showing a reduction of around 5% in the vertical $\beta$-beating around the machine.

The coupling correction using predefined knobs seemed unable to correct coupling to the usual levels. After observing a complex longitudinal structure in the $f_{1001}$ resonant driving term of Beam 1, see Figure 4, it was decided to apply an arc-by-arc coupling correction (with knob name:
*2017_Coupling_Flat_ArcByArc_B1*). This correction uses all available arc skew quadrupole families to minimize both $f_{1001}$ and $f_{1010}$. The effect of this correction is also shown in Figure 4.

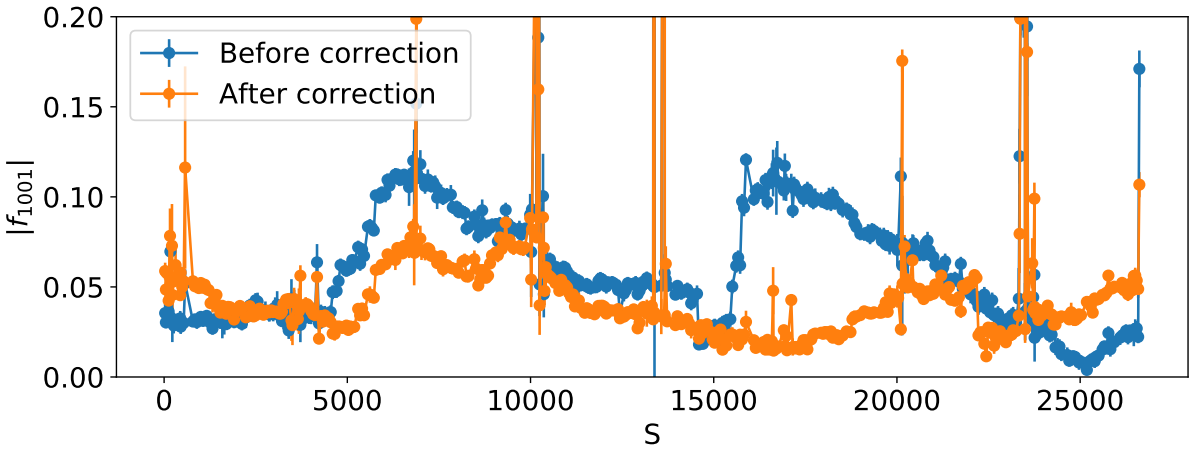


Figure 4: Measured $|f_{1001}|$ before and after the arc-by-arc coupling correction.

K-modulation was then performed in IP1 and IP5 to measure $\beta^*$. Table 6 shows the $\beta^*$, waist displacement and phase advance deviation with respect to the model across the IP drift (BPM1L to BPM1R) computed both with K-modulation and AC-dipole ($\Delta\phi(l)_{kmod} = \arctan(\frac{l-w}{\beta^*}) - \arctan(\frac{l+w}{\beta^*}) - \phi(l)_{model}$). This comparison allows to discard the K-modulation measurement in Beam 1 vertical plane of IP5 as it deviates about $10\sigma$ from the AC-dipole measurement. Discarding this value we see a maximum $\beta^*$-beating of up to 12% in the vertical plane of Beam 1.

| | | | $\beta^*$ [m] | waist [m] | $\Delta\phi_{K-mod}$ $[2\pi 10^{-4}]$ | $\Delta\phi_{kicks}$ $[2\pi 10^{-4}]$ |
|---|---|---|---|---|---|---|
| Beam 1 | IP1 | Hor | 0.669 ± 0.001 | -0.016 ± 0.014 | -4.6 ± 0.9 | -1 ± 5 |
| | | Ver | 0.168 ± 0.004 | -0.052 ± 0.005 | -9.8 ± 1.4 | 1 ± 3 |
| | IP5 | Hor | 0.162 ± 0.006 | -0.043 ± 0.009 | 1.0 ± 0.3 | 5 ± 12 |
| | | Ver | 1.45 ± 0.05 | 0.72 ± 0.03 | **-104 ± 8** | -4 ± 13 |
| Beam 2 | IP1 | Hor | 0.620 ± 0.008 | 0.145 ± 0.015 | 4 ± 2 | 11 ± 9 |
| | | Ver | 0.157 ± 0.002 | 0.017 ± 0.006 | 0.0 ± 0.4 | 10 ± 12 |
| | IP5 | Hor | 0.147 ± 0.002 | 0.025 ± 0.004 | 2.3 ± 0.1 | 0 ± 8 |
| | | Ver | 0.644 ± 0.006 | -0.101 ± 0.017 | 1.1 ± 1.5 | - |

Table 6: K-modulation measurement at $\beta^*$=60/15 cm after the local correction. The table also shows the phase advance deviation with respect to the model across the IP (BPM1 left to BPM1 right) computed using both the K-modulation results and the measurement form AC-dipoles and ADT kicks, showing in bold a large deviation in one of the K-modulation measurements, making more evident that Beam IP5 vertical K-modulation was a bad measurement. The vertical phase measurement in IP5 of Beam 2 is not available due to a missing BPM.

Having still more than 20% $\beta$-beating in Beam 1, it was decided to compute a global correction in Beam 1. Its effect is shown in Figure 5 (knob name: *2017_Global_Flat_wKmod_B1*).

The high $\beta$-beating wave that appears in the horizontal plane around the arc 45 seemed mostly unaffected by the corrections implemented. This uncorrected wave was also observed at $\beta^*$=10 cm MD [6] and any traditional correction attempt in this region does not seem to improve the situation.

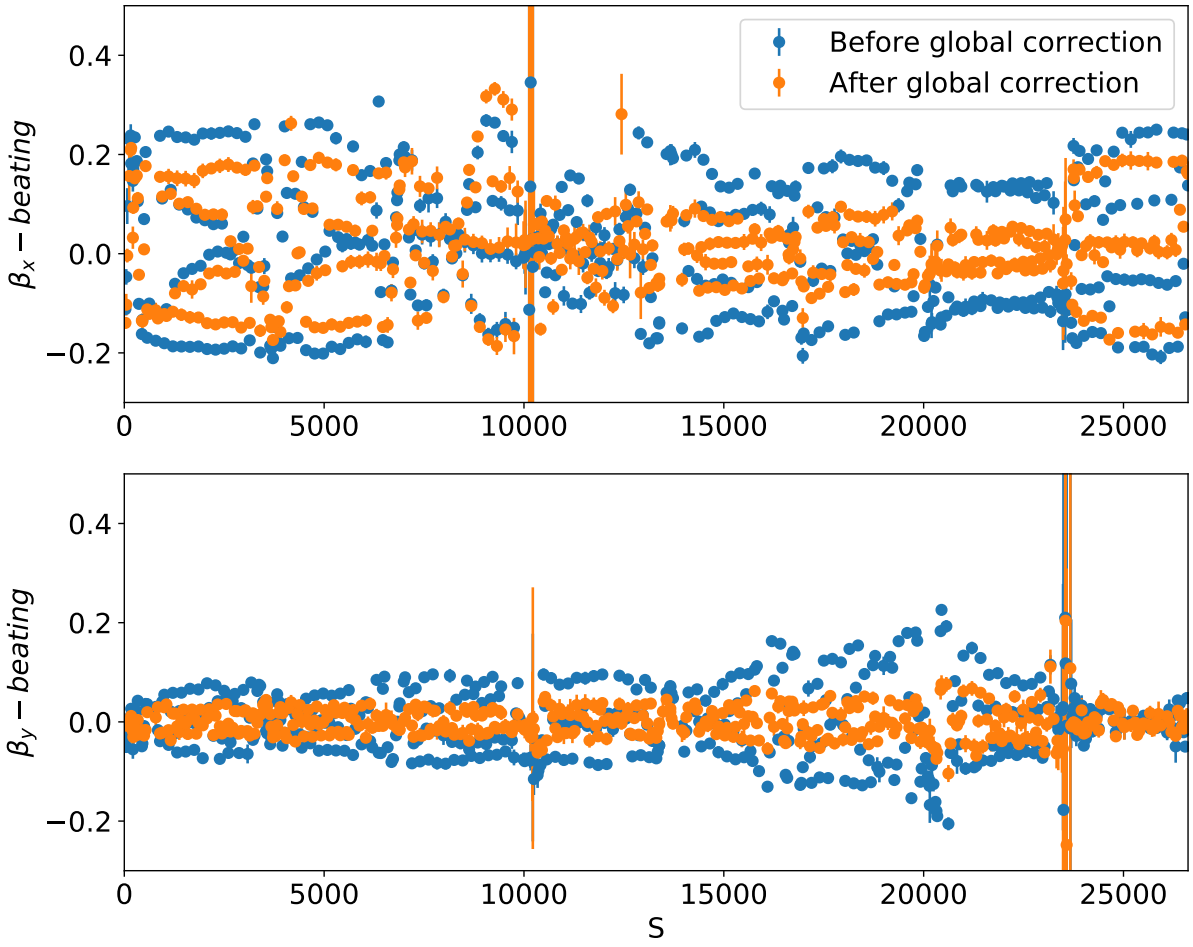


Figure 5: Effect of the global correction in $\beta$-beating.

Using ADT kicks, a $\beta$-beating wave of almost 60% was observed in the arc 81 of Beam 2 in the vertical plane. The optics measurement from the kicks of the ADT seemed of enough quality to compute a global correction also for Beam 2. The correction was trimmed (with knob name: *2017_global_flat_b2*) and the optics was measured again showing a reduction of the $\beta$-beating down to about 20%, see Figure 6.

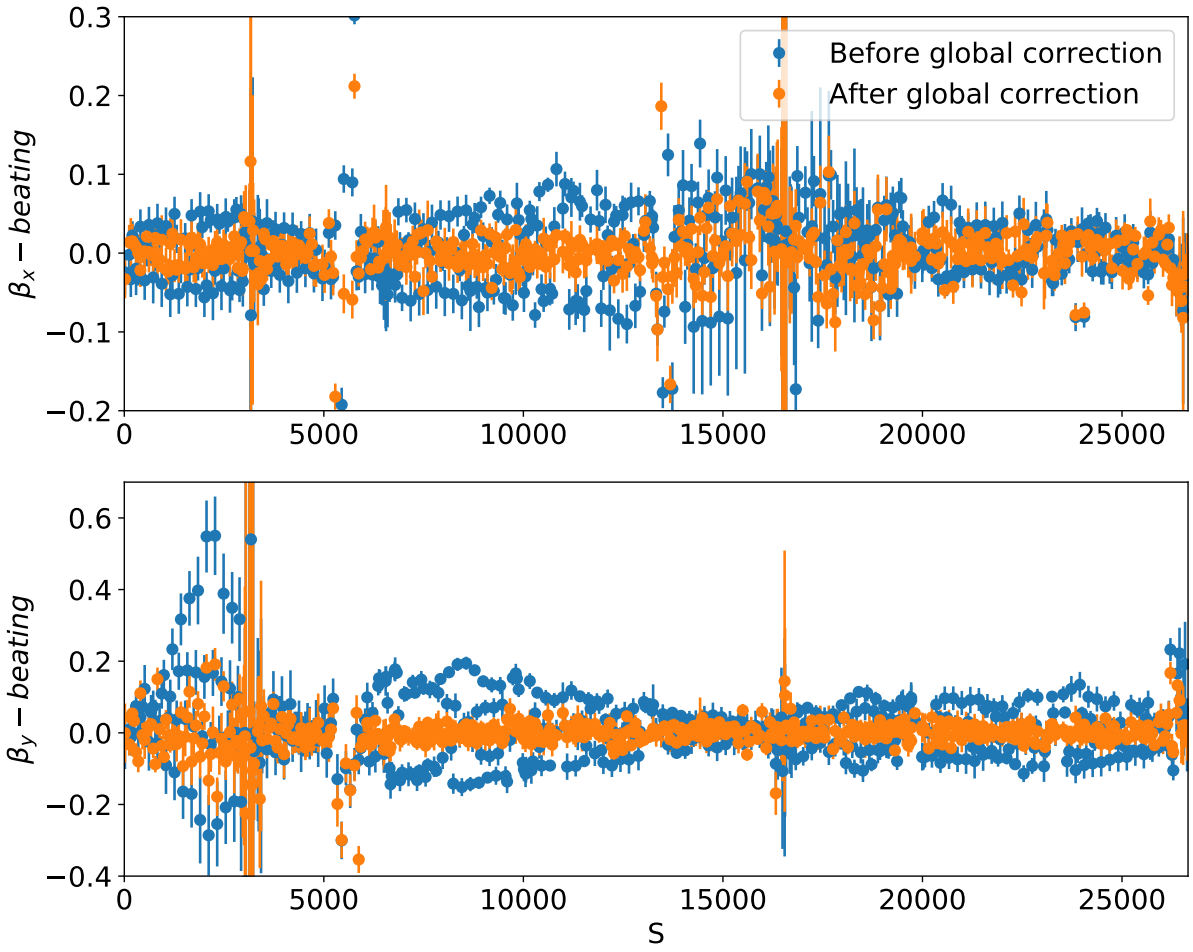


Figure 6: Effect of the global correction in $\beta$-beating of Beam 2 measured using ADT AC-dipole kicks.

K-modulation was performed at the end of the MD to validate the $\beta^*$ after the corrections. Unfortunately, the modulation of IP1 unexpectedly stopped because of problems with the K-modulation application. The results for IP5 are shown in Table 7 still showing the large deviation in the vertical plane of Beam 1 in IP5 observed before corrections. These measurements could not be repeated due to time constraints.

The data from the kicks of Beam 1 was also used to measure the W-function, as shown in Figure 7[10].

| | | | $\beta^*$ [m] | waist [m] | $\Delta\phi_{K-mod}$ $[2\pi 10^{-4}]$ | $\Delta\phi_{kicks}$ $[2\pi 10^{-4}]$ |
|---|---|---|---|---|---|---|
| Beam 1 | IP5 | Hor | 0.174 ± 0.006 | -0.060 ± 0.007 | 0.5 ± 0.5 | 5 ± 12 |
| | | Ver | 1.168 ± 0.056 | 0.573 ± 0.033 | **-79 ± 10** | -4 ± 12 |
| Beam 2 | IP5 | Hor | 0.157 ± 0.003 | 0.037 ± 0.005 | -1 ± 7 | 5 ± 9 |
| | | Ver | 0.602 ± 0.002 | 0.012 ± 0.018 | 5 ± 6 | - |

Table 7: K-modulation measurement at $\beta^*$=60/15 cm after local and global corrections. IP1 measurement is missing because the modulation failed.

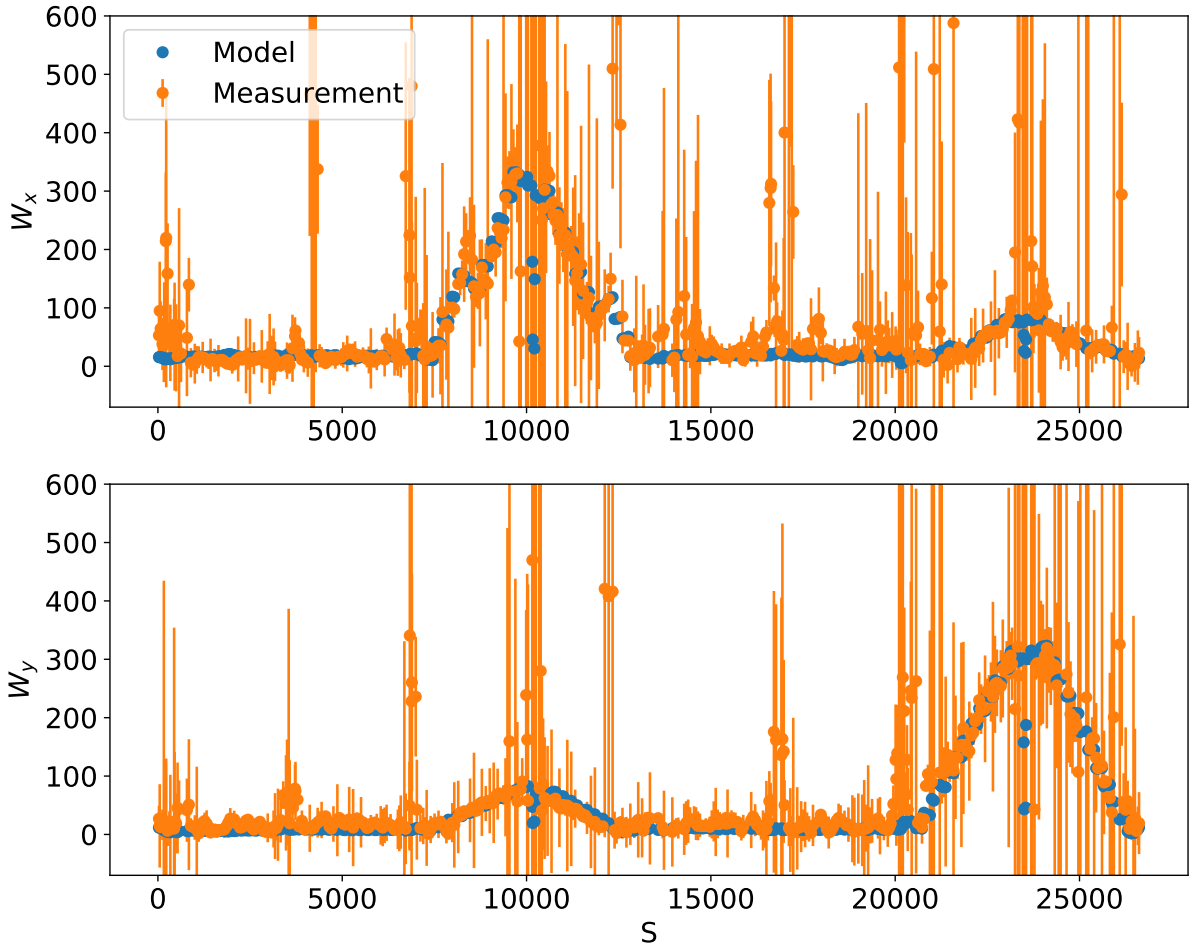


Figure 7: Measurement of the Beam 1 W-function at $\beta^*$=60/15 cm. The model W-function is shown for comparison.

# 4 Spurious $\Delta p/p$

After the end of this MD, due to an error in the operational settings an unexpected deviation in beam momentum of $\Delta p/p$=$1.4 \cdot 10^{-4}$ was found after the trim of the global corrections. Applying this error to the reference model, this deviation was found responsible for around 5% of the peak $\beta$-beating found during the $\beta^*$=60/15 cm measurements after the global corrections, see Figure 8.

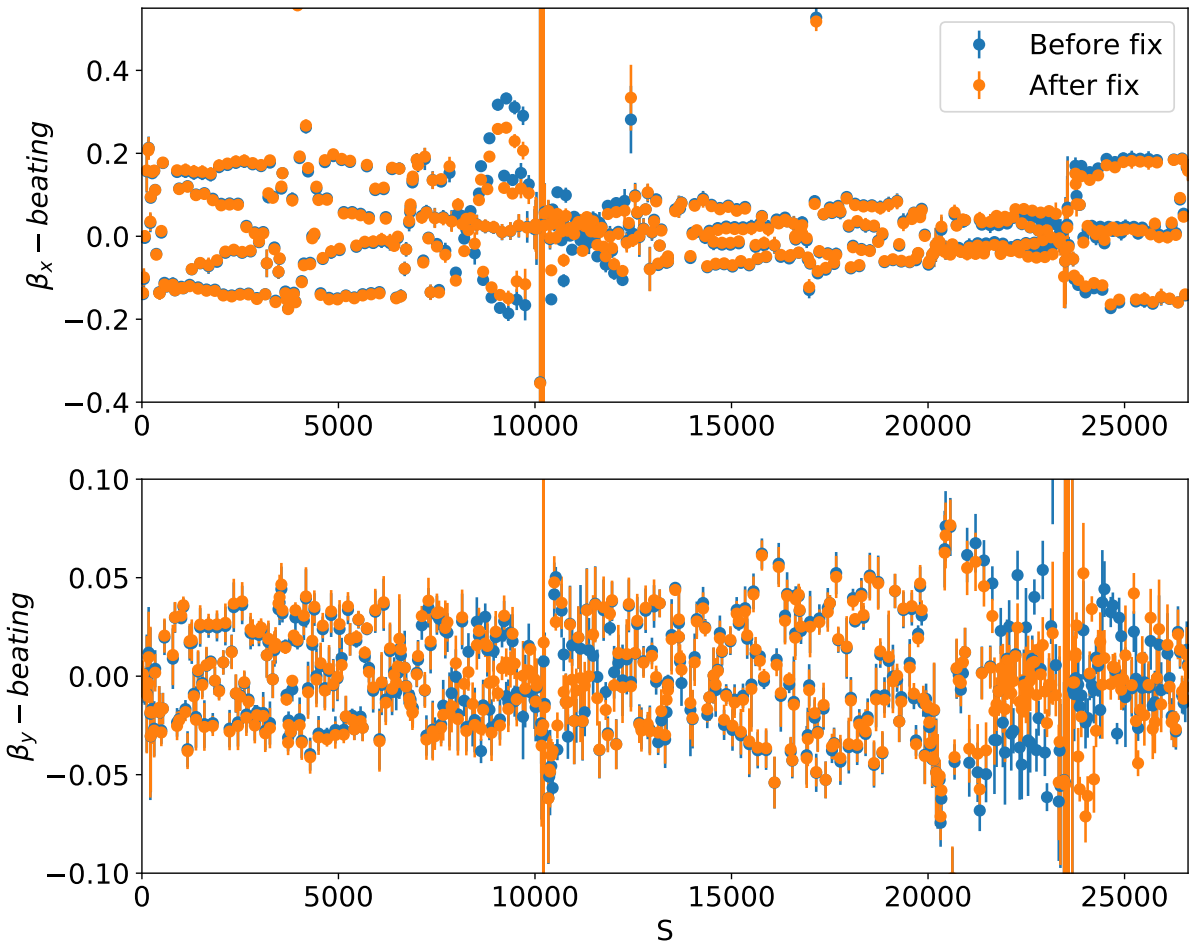


Figure 8: Effect of the $\Delta p/p$ correction in $\beta$-beating after the global correction.

# 5 Conclusion

Flat optics with $\beta^*$=60/15 cm has been proved for the first time for optics corrections. New local errors were observed in IP1 and arc 45. Traditional global correction was unable to correct the $\beta$-beating in the arc 45. After local and global corrections the peak $\beta$-beating was still of about 24% in Beam 1 and about 20% in Beam 2.

All these issues should be closely studied to understand how to correct flat optics in future MDs and in view of HL-LHC.

# References


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