LIMITATIONS ON OPTICS MEASUREMENTS IN THE LHC

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Abstract

In preparation of the optics commissioning at an energy of 6.5 TeV, many improvements have been done to cope with the expected reduced signal to noise ratio due to lowered bunch intensities imposed by machine protection considerations. This included, among others, an increase of the flat top duration of the AC dipole excitations, which allowed to use more turn-by-turn data for the analysis. The longer data acquisition revealed slow drifts of the optics, which limited the increased measurement precision. Furthermore, we will present how orbit drifts influenced dispersion measurements and, as a consequence, posed another limitation for the optics correction. In this paper we will discuss the implications of these observations for the measurement and correction of the optics.

AC DIPOLE PERFORMANCE

During the first long shutdown of the LHC (LS1) the BPM acquisition system and the AC Dipole have been upgraded to allow for 6600 turns of beam excitation plateau and turn-by-turn (TbT) acquisition of bunch position for optics and short-term dynamic aperture measurements [1]. Before LS1 the beam excitation and TbT acquisition were limited to 2200 turns. The increased length of the TbT data allows for a closer look on the optics stability during one beam excitation. To study potential changes over time the measurement files of 6600 turns were split into 2000 turns each, starting from different turn numbers in steps of 500 turns. A noise reduction using the singular value decomposition (SVD) technique was performed on each file separately in order not to add additional correlations among the different windows. One can now look at the evolution over time of observables like the driven (AC dipole) 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 both planes. An increase of the driven tune 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 horizontal plane of Beam 1, where the measured AC dipole tune unexpectedly changes in between turn number 2000 to 3000, also the phase advance uncertainty increases with larger numbers of turns analyzed. It was verified that the reconstructed phases have no associted systematic shift.

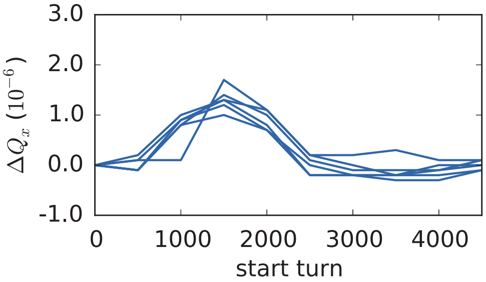

Figure 1: Measured deviation of the AC dipole horizontal Beam 1 tune when 2000 turns out of 6600 were analyzed, starting from different turn numbers. The plots show six different measurements performed at a β^* of 80 cm.

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 (6600 turns of TbT data). One can clearly see, how the longer TbT data acquisition increases the precision of the measured phase advances. Moreover, a significant difference of the uncertainty is visible for the different planes. This can be attributed to the aforementioned possible technical problem with the AC dipole.

ORBIT DRIFTS

In 2015 orbits were subject to drifts with periodicity of approximately 8 h [2]. Several independent analyses have pointed out movement of the triplet quadrupoles in IP8. This

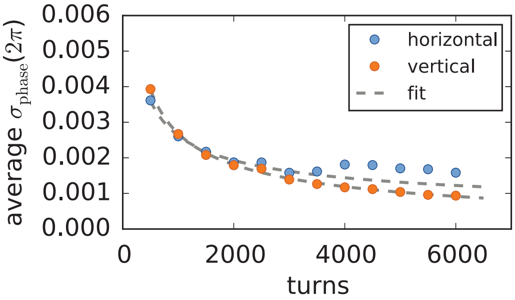

Figure 2: Average precision of the measured phase advance for different number of turns used in the analysis for Beam 1. The fit function is $\alpha/\sqrt{x}$, and for the horizontal plane only the first five data points were used for the fit.

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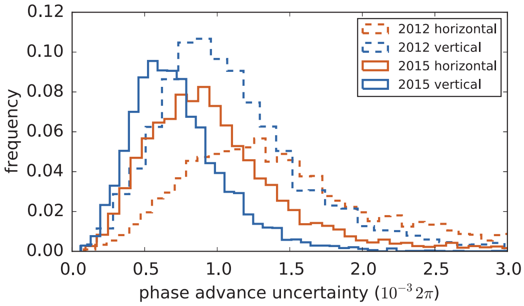

Figure 3: Uncertainties of the measured betatron phase advances for both beams for optics with $\beta^* = 60$ cm (2012) and $\beta^* = 80$ cm (2015).

largely reduced the accuracy of dispersion measurements and consequently of the optics corrections, because during the time the different beam energies were probed the orbit drift was comparable to the changes due to dispersion. It was immediately spotted that the dispersion error bars are much larger than expected. Nevertheless, before the source was identified all orbit change was attributed to the dispersion. In consequence global optics corrections, which aim to correct both dispersion and phase advance, were driven to correct inaccurate measurements.

During 2016 winter shutdown the reason of the movement was traced to cryogenics pressure and temperature regulation and an appropriate stabilization system was introduced. Indeed, afterwards the orbit drifts were no longer observed. The accuracy of dispersion measurements is as expected and it is twice better corrected, see Section ACHIEVED ACCURACY.

β^* AND WAIST CORRECTION

In LHC k-modulation is the preferred technique to measure β^* [3,4]. In 2015 k-modulation measurements revealed that the IP optics was not sufficiently corrected and the waist was shifted away from the interaction points as much as 40 cm [5,6], causing about 5% luminosity loss. Already during the ion optics commissioning in 2015 additional corrections were performed to mitigate this issue [7]. After this experience, the tool for k-modulation measurements was fully automatized to obtain the result right after the measurement [8,9].

The procedures for optics corrections have been extended to include k-modulation measurements at all IPs. The segment-by-segment technique [10–13] performs a matching of the measured phase advance and the beta functions from k-modulation simultaneously, to guarrantee the best local corrections. It needs to be noted that waist location can not be fully corrected at the stage, because the local corrections are worked out with insertion region treated as a transfer line, and for the initial conditions measured Twiss parameters are used. Of course the waist position depends on initial Twiss parameters and therefore the global correction is the proper place to correct the waist. After local corrections are implemented new set of measurements, including k-modulation, is performed. The new algorithm simoultaneously correct the obtained phase advance and β^* errors because it uses response matrix that contains both phase and beta function changes due to variation of every corrector quadrupole.

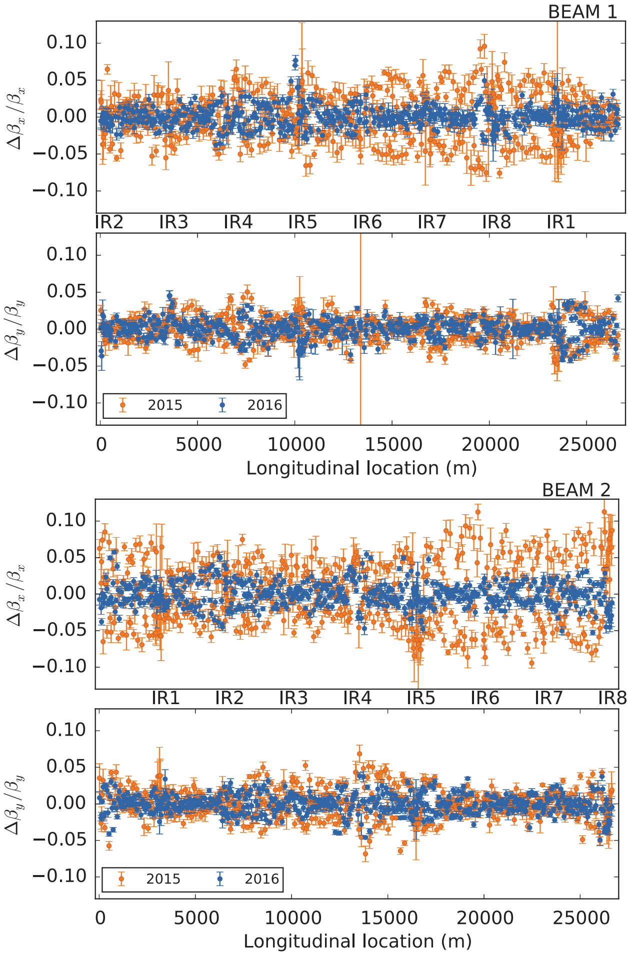

Figure 4: Improvement in β-beating at 40 cm β^*.

The correction algorithm allows to assign specific weights to the phase, dispersion and β^*, in order to find a best compromise. Typically the biggest weight is on β^* and waist position, then on phase advance and the smallest is on dispersion. β from amplitude measurements with calibrated BPMs [14, 15] were also used for the first time during 2016 optics commissionig. These measurements were instrumental for debugging the new k-modulation software while they were not ready to be used in corrections.

ACHIEVED ACCURACY

As a result of the many improvements in the machine and in the LHC optics measurements and corrections algorithms an unprecedented rms β-beating close to the 1% has been achieved in 2016. Figure 4 shows the β-beating for both rings at β^* of 40 cm. The peak and rms values of the β-beating are detailed in Table 1.

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Table 1: Normalized dispersion ($ND = D/\sqrt{\beta}$) and β function beating amplitude and rms (in %) in 2016 and 2015 at 40 cm β^*. Column labeled with B. contains beam number.

	B.	min	max	rms	min	max	rms
			2016			2015	
ND_x	1	-1.7	1.9	0.52	-2.2	2.5	0.78
ND_y	2	-1.8	1.6	0.62	-3.1	2.5	1.19
β_x	1	-3.8	7.7	1.42	-7.6	9.6	3.18
β_y	1	-4.2	4.5	1.35	-4.8	5.0	1.69
β_x	2	-5.3	5.8	1.79	-9.5	11.3	4.24
β_y	2	-4.9	3.8	1.42	-6.8	6.8	2.07

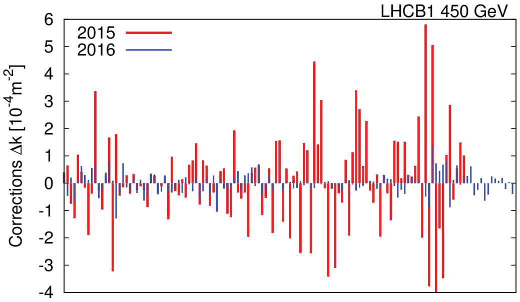

Figure 5: Corrections strength at injection in 2015 and 2016.

In 2015 corrections at injection were quite strong and this year a better result is obtained with much smaller adjustments, see Figure 5. It was verified that the beating of the machine before any corrections is very similar to the previous year, and we conclude that weaker corrections are thanks to the dispersion measurements that are much more accurate and are not polluted by the triplet magnet movements. Naturally, also the dispersion has been better corrected, see Figure 6 and Table 1. It is specially visible for Beam 2, for which the beaing in 2015 was 50% larger than for Beam 1, while in 2016 it is at very similar level. Apparently the dispersion pattern that we attempted to correct in 2015 was more affected by the orbit drifts.

Table 2: Measured Values of β^* in IP 1 and 5

IP	Beam	β^*_x [m]	$\sigma_{\beta^*_x}$ [m]	β^*_y [m]	$\sigma_{\beta^*_y}$ [m]
1	1	0.397	0.007	0.401	0.002
1	2	0.397	0.002	0.402	0.001
5	1	0.399	0.003	0.401	0.001
5	2	0.394	0.003	0.397	0.004

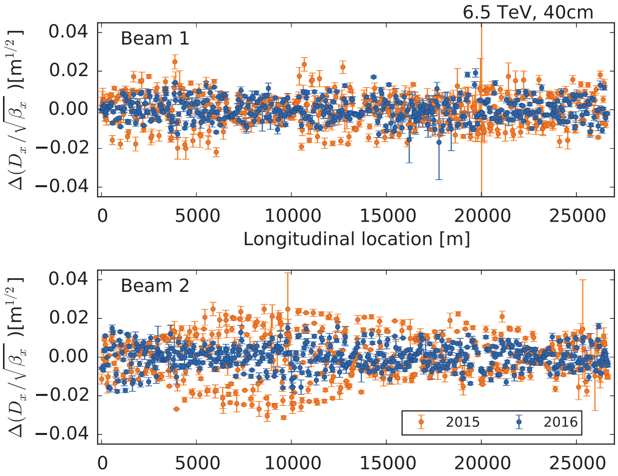

Figure 6: Improvement in dispersion beating at 40 cm β^*.

The measured β^* and waist position at the two lowest β^* interaction points are summarized in Tables 2 and 3, repectively. The measurement was done at injection tunes 0.28 and 0.31, while during collisions the tunes are 0.31 and 0.32. The k-modulation measurement can not be performed at collision tunes becuase of vicinity of the 3rd order resonance line that would be crossed. Therefore, the measured values were propagated to the nominal working point with help of the model. The biggest β^* deviation from 40 cm is 0.6 cm and waists are within 6 cm from the interaction points.

Table 3: Measured Values of Waist Offset in IP 1 and 5

IP	Beam	w_x[cm]	σ_{w_x}[cm]	w_y[cm]	σ_{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

CONCLUSIONS

Several limitations affected the optics measurements and corrections in the LHC during 2015. The stability of the orbit and of the optics measurements and correction techniques were largely improved in 2016. As a result of these improvements an unprecedented rms β-beating close to the 1% has been achieved in 2016.

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