RECORD LOW β-BEAT OF 10% IN THE LHC

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Abstract

During the 2011 LHC run several measurements and correction campaigns were conducted. As a result a peak β-beat of 10% level was achieved. This level, well below the specified tolerances of the LHC, improves the aperture margins and helps minimize the luminosity imbalance between the different experiments. A combination of local corrections at the insertion regions and an overall global correction were used to achieve this record low beta-beat. The sequence of the optics corrections and stability along the 2011 run are reported.

INTRODUCTION

Design tolerances for the LHC optics are tight. To cope with these tolerances specific tools and algorithms were developed. In 2010 a first correction campaign was carried out [1]. A peak β-beat of $\sim 15\%$ was achieved for beam 2. For 2011 different optics settings were explored with respect to 2010. The β^* for IP_1 and IP_5 was squeezed to a value of 1.5 m, $IP_8 = 3$m and IP_2 remained at injection settings. Measurements were performed using AC-dipole kickers. AC-dipole kicker was used to introduce transverse oscillations. 2250 turn-by-turn data were acquired . An interpolated FFT, such as SUSSIX [2] and SVD [3] algorithms are used to calculate phase and amplitude of the main betatron line to compute the optics parameters.

OVERVIEW

An overview of the applied corrections is shown in figure 1. The optics measurement and correction campaign in 2011 was done in 10 days. Peak β-beat of 20%, 60% respectively in horizontal and vertical plane for beam 1 was observed , shown in figure 2. For beam 2 a peak β-beat of 30%, 25% was observed, respectively for the horizontal and vertical plane, shown in figure 3. Red dots show the original measured β-beat before any corrections were applied. Large β-beat variations are observed for both beams indicating that local error sources are present. After applying local corrections the observed local jumps were reduced significantly, shown by the green dots in figures 2 and 3. Peak β-beat for beam 1 was reduced to 20%, 15% respectively for horizontal and vertical plane. For beam 2 to 20% in both planes. Global corrections were applied for both beams separately, this was possible as no common correctors were used. A peak β-beat of 10% is achieved for both planes in both beams, shown by blue dots. This result is achieved thanks to a thorough magnetic measure-

ment campaign and sorting (i.e the installation of the magnets in the ring to minimize the effect of magnetic errors).
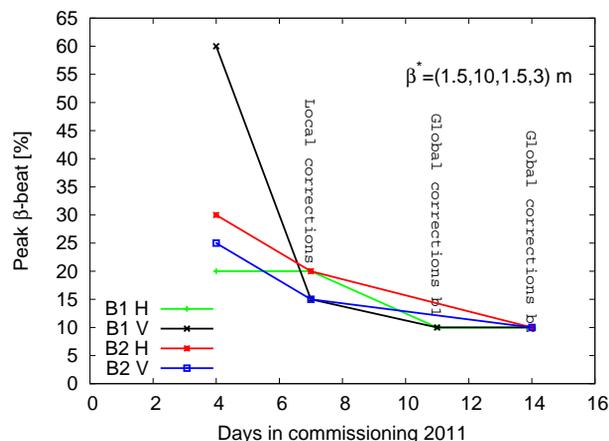

Figure 1: Overview of the applied corrections for the 2011 optics. Days in commissioning, horizontal axis, and measured peak β-beat , on the vertical axis. First measurements indicated a peak β-beat of 60%, 30% respectively in the horizontal and vertical plane of beam 1. By applying local and subsequently global corrections the peak β-beat was reduced to a 10% level for both planes in both beams.

LOCAL CORRECTIONS

An illustration of a local correction in IP_5 is shown in figure 4. The local correction was calculated using the segment-by-segment technique [4]. The phase error, i.e. the difference in the phase advance between measurement and model, is shown. The phase advance is defined as the difference in phase between the ith BPM and the first BPM in the segment. The top plot is the phase error in the horizontal plane and below the vertical plane. The red line shows the measured error before local corrections were applied. The black line is the fitted model, this is achieved by applying ktqx2.l5$= -1.0e^{-5}$ and ktqx2.r5$= -1.3e^{-5}$ to the local model to fit the measurements. Blue line is the measured total phase error after applying local correction in IP_5. The error which was observed is reduced significantly. The implemented correction is not perfect, as the ktqx correctors are common for both beams. In this case a suitable correction for both beams had to be found. The triplet were identified as the leading sources for the β-beat.
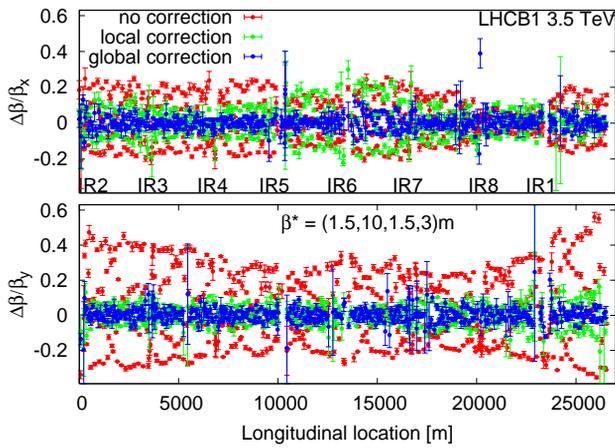
Figure 2: β-beat for beam 1, horizontal plane above and vertical plane below. Three colors represents the β-beat measured at the different steps during the correction process. Red, virgin machine no corrections applied. Green, after applying local corrections and blue after both local and global corrections were applied.
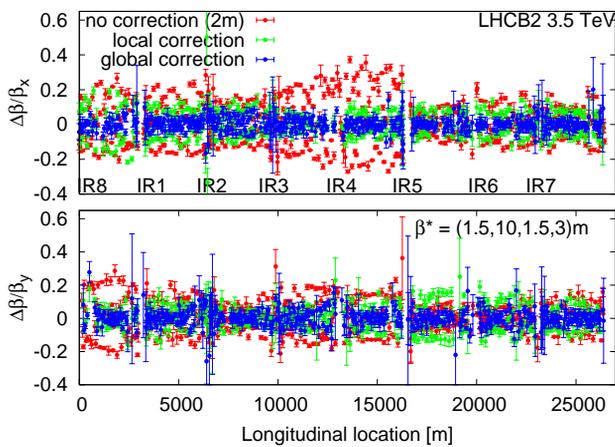

Figure 3: β-beat for beam 2, horizontal plane above and vertical plane below. Three colors represents the β-beat measured at the different steps during the correction process. Red, virgin machine no corrections applied. Green, after applying local corrections and blue after both local and global corrections were applied.

The corrections were based on values found for the correction in 2010. Table 1 shows values for implemented local corrections for the triplets at IP_1, IP_5 and IP_8. Two correctors (kq9.l1b1 and kq5.l6b2), one per beam, were additionally used to achieve a better corrections in the beams separately. These two additional correctors are the largest correctors implemented.

Corrector	$\Delta K\ [10^{-5}m^{-2}]$	Relative [%]
kq9.l1b1	3.8	-0.60
ktqx2.r1	-0.8	0.09
ktqx2.l5	1.0	0.11
ktqx2.r5	1.3	-0.15
kq5.l6b2	-4.6	0.70
ktqx2.l8	-2.3	0.26
ktqx2.r8	-0.5	-0.06

Table 1: Implemented local corrections are listed. The ktqx magnets, common for both beam, are trim quadruples nested in the triplets at the interaction point. Two correctors (kq9.l1b1 and kq5.l6b2), one per beam, were additionally used to achieve a better correction in the beams separately. These two additional correctors are the largest correctors implemented.
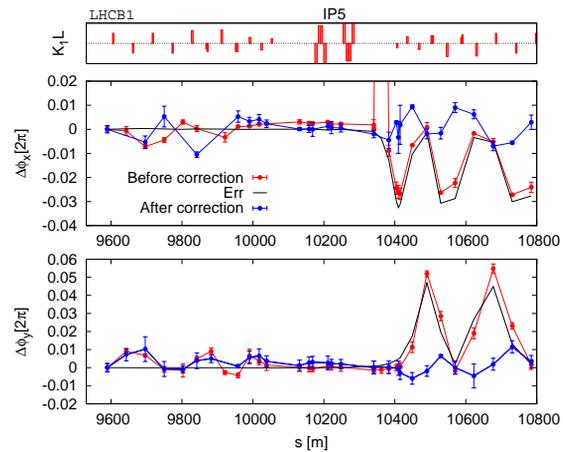

Figure 4: Illustration for local correction in IP_5 using the segment-by-segment technique. After 10400 m the phase starts deviating, right after the triplet, indicating that there is a large error present in the triplet, red line. A correction was calculated using trim quadrupoles in the triplets, ktqx, left and right from the IP. Measurements conducted afterwards confirm that the implemented correction was successful, blue line. The error has been reduced significantly.

GLOBAL CORRECTIONS

Global corrections for beam 1 and beam 2 were implemented separately. Only correctors acting on one beam were used. Figure 5 shows a distribution of the implemented correctors along the ring. The top plot show the distribution for beam 1 , bottom plot for beam 2. For beam 2 the distribution for both 2010 and 2011 is shown. No global correction was implemented for beam 1 during the correction campaign in 2010. A total of 95 and 112 correctors were used respectively for beam 1 and beam 2 to reduce the β-beat to a 10% level. The maximal strengths for both beams, $0.8e^{-4}m^{-2}$, are located around IR 1.
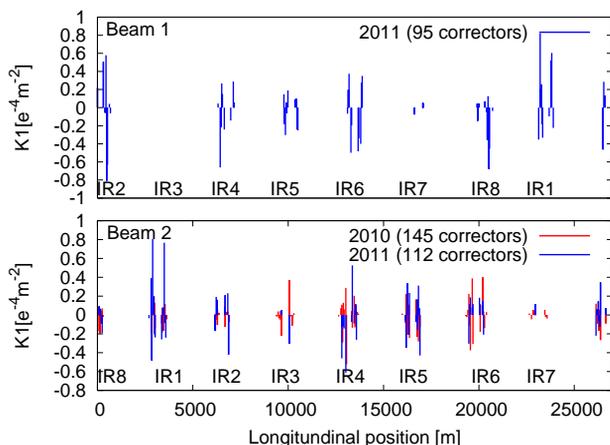
Figure 5: Distribution of correctors along the ring for beam 1 in 2011, top and beam 2 in 2010 (red) and 2011 (blue), bottom. The correctors are trim quadrupoles, no common correctors were used. For beam 1 no global correction was applied in 2010. It can be observed that largest corrector strengths applied are around IP_1 for both beams.

MEASUREMENT RESOLUTION

A histogram for the measurement error on the β function is shown in figure 6. Data is shown for injection, $\beta^* = 3.5$ m and $\beta^* = 1.5$ m. Most of the errors are below 5%. As the error on the optics measurement cannot be better than 5%, reaching β-beat below 10% remains a challenge.
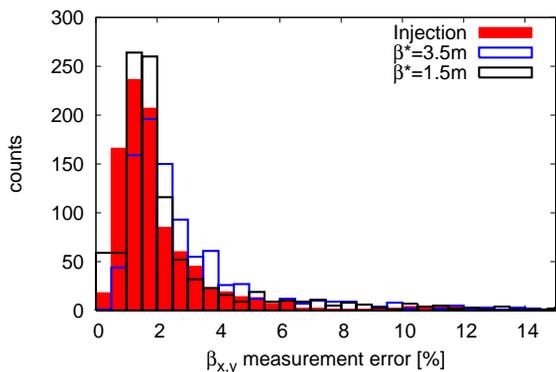

Figure 6: Histogram of the measurement error on β function. Different measurement are shown for injection, $\beta^* = 3.5$ m and $\beta^* = 1.5$ m. The main distribution of the errors is below 5%. As the error on the optics measurement cannot be better than 5%, reaching β-beat below 10% remains a challenge.

CONCLUSIONS AND OUTLOOK

A record low β-beat of $\sim 10\%$ in a superconducting hadron machine has been achieved, well below tolerances. This was achieved by applying first local corrections at

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the triplets and subsequently global corrections to correct small distributed errors that cannot be corrected using the segment-by-segment technique.
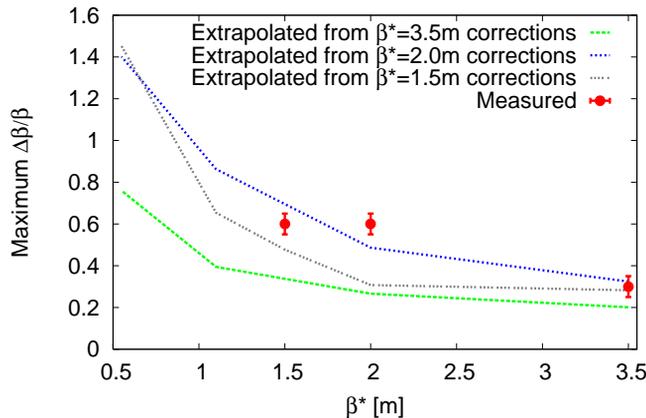

Figure 7: Extrapolated errors to a lower β^* are shown. Only the observed local errors at different β^* settings are included in the extrapolation. Red dots show the measured peak β-beat at the different β^* settings. Lines represents extrapolation for different settings. For $\beta^* = 1.5$m only IP_1, IP_5 and $IP_8 = 3$ m are squeezed. For the operational settings of 2010, all IPs were squeezed to a β^* value of 2 m and later 3.5 m. It can be observed that the challenge remains for $\beta^* = 0.55$ m. Dedicated local and global corrections will be needed to correct the optics to a satisfactory level.

The machine is operating at intermediate energy. Extrapolated errors to a lower β^* are shown in figure 7. Only the observed local errors at different β^* settings are included in the extrapolation. The red dots show the measured peak β-beat at different β^* settings. The different lines represent the extrapolated error for different optics settings. It is clear from the plot that the challenge remains for $\beta^* = 0.55$ m. Dedicated local and global corrections will be needed to correct the optics to a satisfactory level.

ACKNOWLEDGMENTS

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