OPTICS PERFORMANCE OF THE LHC DURING THE 2012 RUN

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Abstract

During 2012 the LHC was operating at 4TeV with beta star at ATLAS and CMS interaction points of 0.6 m. During dedicated machine studies the nominal LHC optics was also setup with beta star of 0.4 m. A huge effort was put into the optics commissioning leading to a record low peak beta-beating of around 7%. We describe the correction procedures and discuss the measurement results.

LINEAR OPTICS CORRECTION

LHC must have extremely good control of the optics not only due to the huge power of the beams, but also to deliver similar luminosities for ATLAS and CMS experiments. It was therefore decided to place special attention to the optics commissioning during last runs. The machine was measured in the absence of any beam-based corrections (*virgin* machine) throughout the entire magnetic cycle. To reduce the measurement uncertainty compared to previous years the excitation amplitude of the AC dipole was increased. First, new local IR corrections were computed, which remain constant throughout the beta squeeze process. Next, global corrections were applied to minimize β-beating and dispersion beating simultaneously. Finally, local β^* and IP waist knobs were used to equalize luminosities where required. These knobs use independently powered quadrupoles excluding the triplet quadrupoles as these ones act on both beams.

Local corrections are best suited for the IRs where the β functions are large and there are independently powered quadrupoles. However, the small phase advance between quadrupoles introduces some degeneracy in the possible corrections. To minimize the level of degeneracy, multiple optics were corrected simultaneously for both beams. Figure 1 shows an illustration of a simultaneous correction for six different optics (three per beam) using the segment-by-segment technique [1] for IR5. The good quality of the corrections, as illustrated in Fig. 1, in this tightly constrained scenario provides confidence in this approach.

Global corrections are required to take care of the optics errors in the arcs and the residuals from the IR local corrections. All available singly powered quadrupoles were used to minimize the β-beating and the normalized dispersion beating at all BPMs in an inverse response matrix approach. Figure 2 shows the evolution of the β-beating along the squeeze after local and global corrections. The record low β-beating of about 7% is reached for β^*= 0.6 m; see [1] for further details.

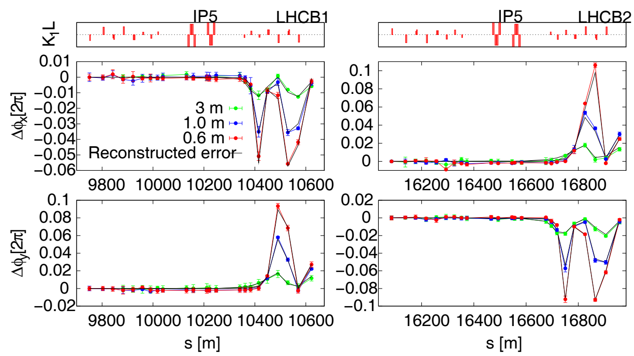

Figure 1: Illustration of the segment-by-segment technique applied to IR5 simultaneously to the two beams and three different β^*. The black lines show the reconstructed error model.

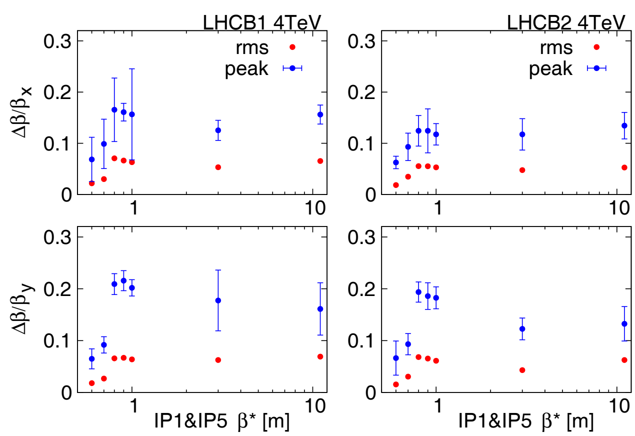

Figure 2: β-beating after local and global corrections along the squeeze. Beam 1 (left) and Beam 2 (right), horizontal (top) and vertical (bottom) plots showing the peak and rms β-beating values versus β^*.

MEASUREMENTS AND CHECKS

Polarity Checks Polarities and strengths of the focusing and defocusing octupoles, spool piece octupole correctors, arc skew sextupole correctors and interaction region sextupoles have been extensively checked [2]. The polarity of each octupole group in each arc was verified by trimming one group and measuring the resulting change in second order chromaticity. In each case the measured second order chromaticity agreed well with predicted value, indicating that all octupoles have the correct polarity.

* Work supported by the European Commission within the oPAC project under Grant Agreement 289485

ISBN 978-3-95450-122-9

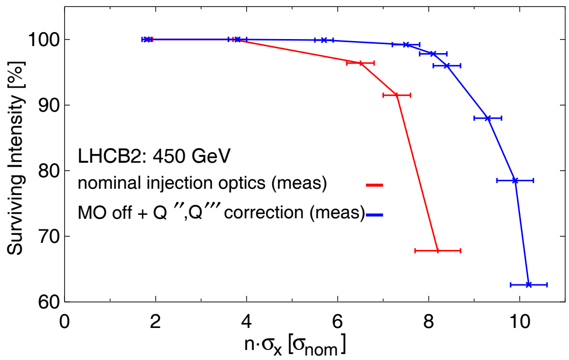

Figure 3: Surviving beam intensity 30 seconds after a transverse kick versus the kick amplitude before (red) and after correction (blue).

Each arc contains four skew sextupoles powered in series that were checked by measuring the change to chromatic coupling when a magnet family was trimmed. A comparison of the measured chromatic coupling with model predictions indicated that all measured MSS magnets have reversed polarity.

Each interaction region contains pairs of normal and skew sextupole correctors. The polarities of the skew sextupoles in IR1, where the crossing angle is vertical, and the normal sextupoles in IR5, where the crossing angle is horizontal, were verified by trimming the magnets and measuring the resulting tune shifts. Comparison of the measured tune shifts with model predictions showed that the polarities are correct.

Dynamic Aperture Measurement at Injection Nonlinear optics studies were performed on Beam 2 at injection energy [3, 4]. The Aperture Kicker was used to excite high amplitude betatron oscillations for the measurement of the dynamic aperture (DA) and first and second order anharmonicities. Measurements were performed on the nominal injection settings, and with the Landau octupoles off and Q'' and Q''' corrections applied to obtain the most linear machine as possible. DA was determined measuring losses as function of the excitation amplitude. Figure 3 shows the surviving beam intensity following horizontal excitation with the kicker versus the amplitude of excitation. Later in 2012 the polarity of the Landau octupoles were reversed for operation. SIXTRACK simulations using the most accurate LHC model gave roughly 3 σ larger DA for the new setting of the octupoles.

Measurement of Amplitude Detuning The amplitude detuning is a critical parameter for the understanding and control of beam instabilities. Yet, measuring the amplitude detuning at top energy represents a real challenge as the only available exciters that can provide a few sigmas oscillation are the AC dipoles. Furthermore, they force oscillations at frequencies different from the natural tunes of the machine and, ideally, the machine tunes should not be excited during the flat-top. We relied on the residual

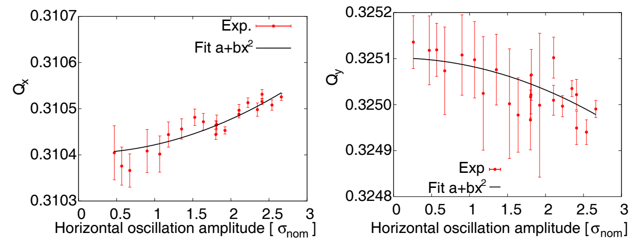

Figure 4: Beam 2 amplitude detuning versus the horizontal oscillation amplitude.

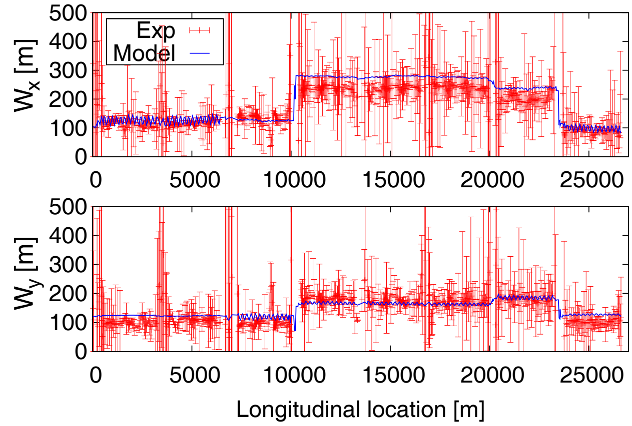

Figure 5: Chromatic β-beating (Montague function) for the nominal LHC optics at β^*=0.4 m compared to the model prediction (blue line).

non-adiabaticity of the AC dipole ramping process to measure the tunes. The actual observation of the machine tunes required aggressive cleaning using SVD techniques. Figure 4 shows example of the measured horizontal and vertical tunes for beam 2. All the details can be found in [5]. This represents the first successful direct measurement of amplitude detuning with AC dipoles. The comparison to model predictions is under study.

Optics Measurements at β^*=0.4 m During MDs two different optics featuring β^*=0.4 m were tested and measured in the LHC. One optics corresponds to the continuation of the nominal squeeze and the other uses the ATS [6]. In both cases IR local corrections were implemented. Global corrections were considered less critical and, consequently, they were not applied. The β-beating from both these optics is at acceptable levels of 20% β-beating.

The off-momentum optics aberrations have been a concern for the LHC machine protection at low β^* values since these could degrade the collimation performance. Figure 5 shows direct measurement of the off-momentum β-beating for the nominal optics at β^*=0.4 m, which is in very good agreement with the model prediction.

CORRECTIONS

Coupling Correction The global coupling knobs for Beam 2 were optimized using computer simulations in-

ISBN 978-3-95450-122-9

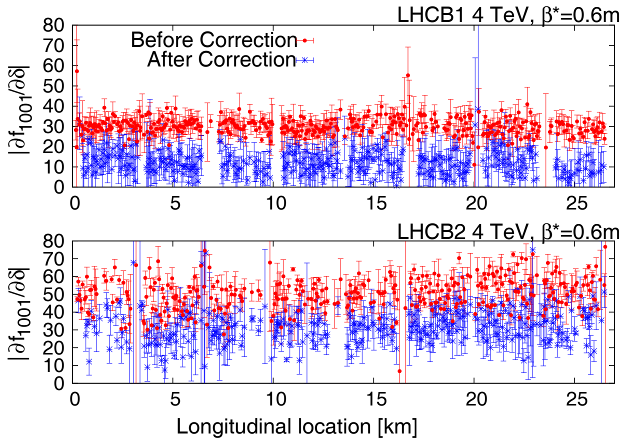

Figure 6: First chromatic coupling correction in the LHC for Beam 1 (top) and Beam 2 (bottom).

creasing their orthogonality to the complex space of f_{1001} and minimizing required skew quadrupole strength [7]. Measurements of the the virgin machine were used to calculate new local coupling corrections. The local corrections remained constant throughout the magnetic cycle and did not change over the year. This is of big importance, because the use of the global knobs requires that the strong local sources are corrected. The global knobs are used iteratively. The best setting is found by minimizing measured $|C^-|$ for different knob settings. This can be a time consuming operation. The fact that the measurement is based on a single pickup is also a limiting factor, because minimizing the coupling at this location might not be the same as minimizing the coupling globally.

In 2012 a new software tool to measure the coupling from the injection oscillations was developed [8]. From the measured f_{1001} the optimum setting for the coupling knobs are calculated and presented in the software. Both parts of the f_{1001} can be corrected simultaneously in normal operation. They were proven successful as the results were in good agreement with the values measured with the Tune Viewer system. We were able to reduce the $|C^-|$ by about factor 4.

Chromatic Coupling Correction The systematic skew sextupole components in the dipoles are known to cause significant chromatic coupling if left uncorrected. There are several skew sextupoles installed to compensate for this known systematic effect [9]. The spurious skew sextupole errors will produce additional chromatic coupling since the dispersion is large in horizontal. Normal sextupoles produce chromatic coupling in regions of vertical dispersion. Once linear coupling is well corrected, chromatic coupling should be corrected as well for optimal machine performance.

In 2012 the first beam based chromatic coupling correction was performed in the LHC. The correction was tested for the nominal 2012 optics, meaning a $\beta^*= 0.6$ m. Beam 2 had 9 independent skew sextupole circuits while Beam 1 had 8 available at this time. In Figure 6 the chromatic coupling before and after correction are presented. The weighted mean value of $\partial f_{1001}/\partial\delta$ was measured to be somewhat larger for Beam 2 than Beam 1, approximately 50 units for beam 2 and 30 units for Beam 1. The chromatic f_{1001} was decreased by about 20 units for both beams, proving that the corrections were successful.

IR Non-linear Correction Non-linear errors in the the LHC IRs may have a significant detrimental impact on lifetime and dynamic aperture. We examinined the feed down to tunes and free coupling for different crossing angles in IP1 and IP5. During dedicated MD time first $a_3 + b_3$ corrections were applied and verified in IR1, then the b_4 correction was added. Measurement and simulation with applied $a_3 + b_3$ correction show a good agreement for both beams (note however that this verifies only the a_3 correction in IP1: the b_3 feeds down to coupling for a vertical excursion). On applying the b_4 correction, measurement and simulation remain in good agreement for Beam 2; however Beam 1 displays a large linear discrepancy in the variation of tune with crossing angle. This may be explained by a $\sim 5\text{mm}$ vertical misalignment of the b_4 corrector with respect to the b_4 sources.

SUMMARY & OUTLOOK

2012 has been an extraordinary year for the LHC Optics Measurement and Corrections. A long list of first time achievements has been accomplished:

1. Record low beta-beating of 7% for hadron colliders
2. First LHC Dynamic Aperture measurement at injection benchmarking simulations
3. First LHC beam-based chromatic coupling correction improving existing model-based corrections
4. First triplet non-linear corrections in LHC
5. First direct measurement of amplitude detuning using AC dipoles.

Furthermore, we believe that all the quadrupole errors above the 1% level have been identified [10] and the magnet databases will be updated for 2015.

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