ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPMP033

LHC RUN 2 OPTICS COMMISSIONING EXPERIENCE IN VIEW OF HL-LHC*

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Abstract

LHC Run 2 has achieved a β^* lower than a factor 2 below design. This has significantly challenged optics measurement and correction techniques in the linear and non-linear regimes, leading to the development of new approaches. Furthermore, experimenting a large variety of optics has allowed facing the difficulties of future optics and gaining understanding of the machine imperfections. A summary of these aspects is given in view of their implications for the HL-LHC Project.

RUN 2

Run 2 was preceded by a successful optics correction campaign in 2012 [1–3] and a thorough development of new algorithms and tools during the first long shutdown [4–7]. Figure 1 shows the minimum β^* deployed in LHC proton physics during Run 2. Achromatic Telescopic Squeeze Optics (ATS) [8] became operational in 2017 starting with no enhancement of the β function in the arcs (tele-index of 1) at β^*=40 cm. The rms β-beating averaged over both beams and both planes is also shown in the bottom plot of Fig. 1. The optics errors had changed between 2012 and 2015, partially due to the energy change, and corrections had to be recomputed from scratch in 2015 [9]. The best optics quality was achieved in 2016 with flat orbit by using K-modulation [10] measurements to recompute corrections. During 2016 measurements with crossing angles revealed that feed-down from higher order magnetic errors in the Interaction Regions (IRs) significantly deteriorated the β-beating but corrections could not be deployed in the middle of the year. Moving to ATS optics slightly deteriorated the optics quality after correction, as seen in Fig. 1 by comparing the 2016 and 2017 measurements with flat orbit. A similar deterioration was observed also in coupling, which originates from the 90° phase advance per cell in four arcs in ATS optics [11]. Since 2017, optics corrections are computed with the crossing angles' operational configuration [12, 13]. The modest improvement in rms β-beating between β^* =40 cm and β^* =30 cm during 2017 is mostly attributed to an improvement in the IR nonlinear corrections which affect β-beating via feed-down. The β from phase measurement was improved in 2017 by replacing MonteCarlo simulations with analytical equations [14]. The optics quality slightly degraded at the smallest β^* ever operational in LHC (β^*=25 cm) partly due to the fact that

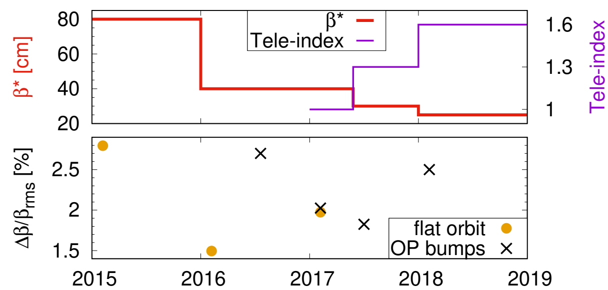

Figure 1: Run 2 at a glance: β^*, tele-index (top) and rms β-beating (bottom) averaged over the two planes and two beams, with and without operational (OP) crossing angle. Note that the 2016 measurement with OP bumps misses one plane out of four.

the corrections from β^*=30 cm were kept without further iterations.

HL-LHC optics commissioning significantly challenges current techniques in terms of efficiency and accuracy due to the large number of optics to be commissioned for luminosity leveling and for the small β^* of 15 cm in the baseline or even the 7.5 cm in the alternative with flat optics and larger tele-index [15]. Some of these aspects are addressed below.

K-MODULATION

K-modulation has been the key technique to measure and correct β^* and waist position during Run 2. Accuracy of K-modulation rapidly degrades with smaller β^* due to the poorer resolution on the tune shift measurement dominated by power supply fluctuations and β functions in triplets and arcs [15–18]. HL-LHC power supply fluctuations yield a tune jitter of 4.2×10^{-5} in the baseline configuration and 2.9×10^{-5} if four main dipoles' power supplies are upgraded. HL-LHC K-modulation simulations predict a 4% accuracy in β^* for a tune uncertainty of 2.5×10^{-5} and 8.5% for 4.2×10^{-5} [18]. To test the assumptions relating power supply fluctuations and tune jitter a measurement campaign was carried out during Run II [19]. Figure 2 shows tune jitter measurements and simulations for different optics at 6.5 TeV. The lowest measured tune jitter of 10^{-5} was found for the ballistic optics, which has IR1 and IR5 triplet quadrupoles switched off [20], in good agreement with simulations. However, in other regular optics with similar expected tune jitter, e.g. β^*=90 m, the measured tune jitter is significantly larger. This suggests triplet quadrupoles as potential sources of extra tune jitter. Globally, in 30% of the cases there is a good

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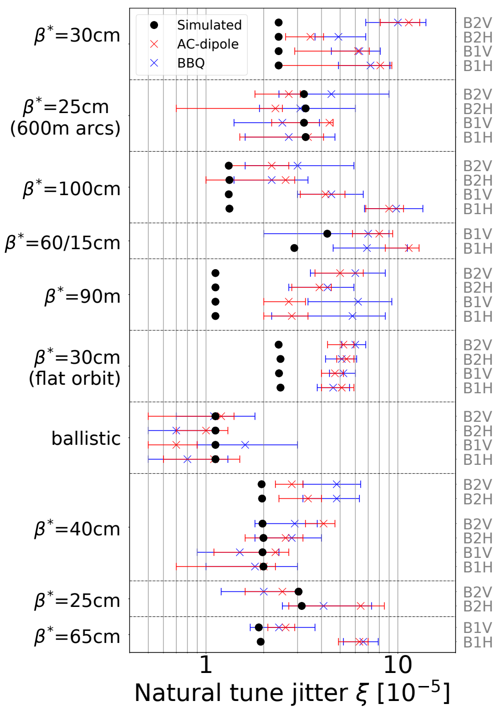

Figure 2: Measured and predicted tune jitter for various optics at 6.5 TeV, from [19]. Optics with $\beta^* < 10$m are ATS.

agreement between measurements and simulations, while a larger tune jitter is measured in the rest of the cases. Therefore there are other sources of tune jitter which have not been identified and considered for estimates in HL-LHC and that will limit β^* control to be above 8.5% in the current HL-LHC baseline. This is largely insufficient to guarantee a luminosity imbalance below 5% between the two high-luminosity detectors.

Alternative or complementary β^* control techniques will be required in HL-LHC. Luminosity waist scans have been experimentally tested in Run 2 demonstrating a superior performance in the measurement of the waist location, as shown in Fig. 3 [21]. Yet, these scans cannot measure the individual β^* in the different planes and beams. Therefore BPMs with better resolution, as DOROS [22], will also be needed in HL-LHC to measure the β at the waist location from the phase advance across the interaction region drift [21]. Optics-measurement-based BPM calibration techniques [23] will be needed to further improve measurement results.

COUPLING AND LUMINOSITY

In 2018 ion operation, the strengths of the left and right skew quadrupole correctors in IR2 were swapped by mistake causing a local coupling bump across the IR. This caused a luminosity loss of about 50%, which was observed by scanning a knob already generated for studies with flat optics [24]. Simulations in [11] show a beam-size growth at the IP that explains about 60% of the observed luminosity loss. Figure 4 plots the relative beam size increase versus

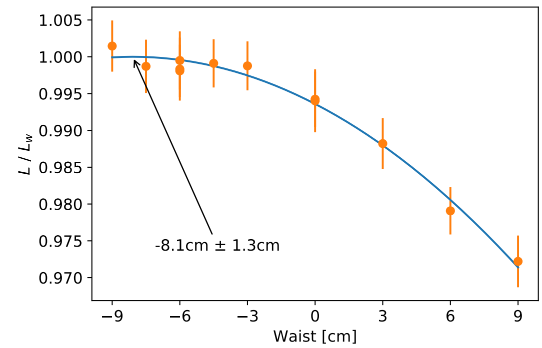

Figure 3: Luminosity versus waist scan as proof-of-principle for accurate waist position measurement, from [21].

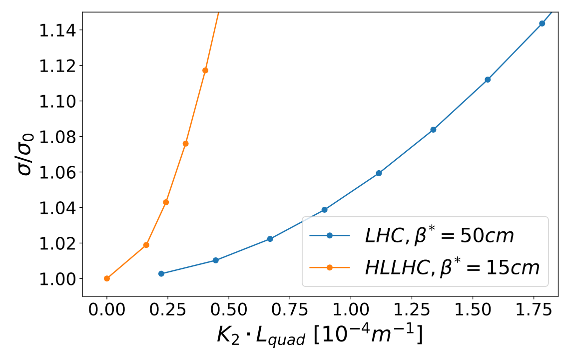

Figure 4: Relative increase in IP beam size from powering the right and left IR skew quadrupoles with opposite sign for LHC and HL-LHC.

such coupling bump for IP2 at $\beta^* = 50$ cm and for HL-LHC at $\beta^* = 15$ cm, showing that local coupling control needs to be about a factor four more accurate in HL-LHC than in LHC. In [11] it is experimentally demonstrated that measurements with rigid waist shifts (meaning all four betatron waists moving simultaneously) allow to break the locality of the coupling bump, making IR coupling errors measurable everywhere. Tolerances need to be evaluated.

NON-LINEAR CORRECTIONS

The baseline plan to power IR non-linear correctors before LHC operation was to use magnetic measurements. However this was already seen as not optimal during Run 1 [2]. Figure 5 compares the best beam-based IR octupolar and sextupolar corrections achieved after various iterations in Run 2 to the magnetic measurements-based predictions. Significant discrepancies are observed in the IR5 normal octupole and in the IR1 skew sextupole corrections. The agreement for the normal sextupole corrections is poor, however, these errors are considered to be small and possibly shadowed by other imperfections. Concerning the discrepancy on the octupolar component in IR5 one possible explanation could be quadrupole misalignments and feed-down from higher order multipoles. From K-modulation measurements it is estimated that beam-to-triplet rms misalignments are in the

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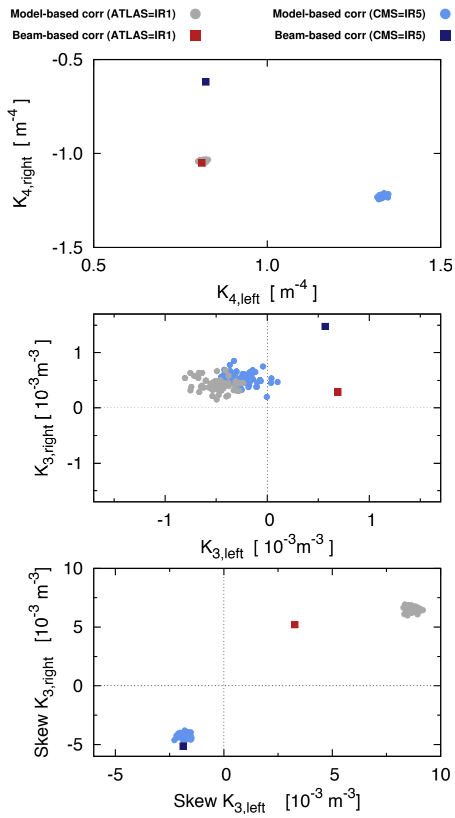

Figure 5: Comparison between beam-based and magnetic measurement-based IR non-linear corrections in 2018.

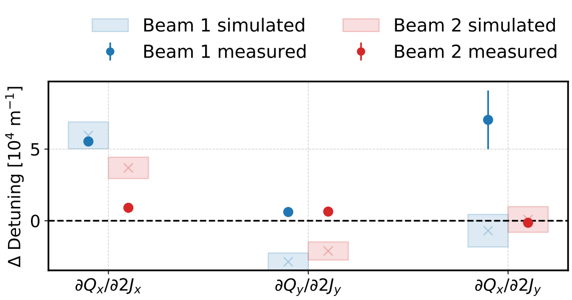

Figure 6: Measured and predicted change in the natural amplitude detuning coefficients from switching on crossing angle in IR5 at β^*=30 cm.

order of 0.3 mm [25, 26]. These offsets only explain about 10% of the discrepancy in the octupolar component.

Skew octupole corrections cannot be compared as done in Fig. 5 since the left skew octupole corrector in IR1 is broken. Since this correction could not be computed locally, a minimization of skew octupolar Resonance Driving Terms (RDTs) was accomplished in Run 2 [27]. Previously normal sextupole and octupole corrections were demonstrated [28, 29] but this is the first time that skew octupolar RDTs are measured and corrected in a synchrotron.

Thanks to the above normal octupole corrections the amplitude detuning was fully suppressed with flat orbit in both beams during Run 2. However, measurements in 2017 and 2018 revealed a large impact of the operational crossing angles on the amplitude detuning coefficients [30, 31], originating from feed-down of the higher order multipolar components in the IR magnets. Figure 6 shows a comparison between measurement and simulation of the amplitude detuning shift due to the crossing angle in IR5. Only two out of the six amplitude detuning coefficients feature good agreement, therefore the current magnetic model is not sufficient to explain observations. Amplitude detuning emerging from crossing angles cannot be corrected using IR octupolar correctors. From simulations, both decapolar and dodecapolar components significantly contribute to the amplitude detuning with crossing angles. However, LHC is not equipped with IR decapolar correctors and only a partial correction could be accomplished using the dodecapolar correctors. There has been significant progress in the measurement of dodecapolar observables [32], however a correction of the LHC triplet dodecapole errors has not yet been established.

Poor non-linear corrections in HL-LHC can challenge linear optics measurements and corrections as the dynamic aperture of particles undergoing forced oscillations is typically significantly lower than free dynamic aperture [33]. This means that the usual forced oscillations applied to measure linear optics could cause severe beam losses and emittance growth stopping the measurement.

OUTLOOK

Run 2 has uncovered new challenges for optics control in LHC and its luminosity upgrade. Run 3 should therefore be used to progress in the development of techniques to guarantee the HL-LHC success as: (i) extended, faster and more efficient optics measurement [34, 35] and corrections to cope with β^* leveling including software improvements [36–43]; (ii) monitor tune jitter as a potential limitation of K-modulation; (iii) efficient luminosity scans for the measurement of β waist offsets and test local coupling corrections; (iv) exploitation of the high resolution DOROS BPMs for measuring the β at the waist location; (v) incorporation of orbit bumps in the arcs as optics correctors; (vi) generalize the use of RDTs for IR non-linear corrections; (vii) streamline crossing angle scans and amplitude detuning measurements; (viii) address the IR dodecapolar correction.

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