Nonlinear optics commissioning in the LHC

E.H. Maclean, X. Buffat, F. Carlier, E. Fol, L. Malina T.H.B Persson, J. Coello de Portugal, R. Tomás,
P.K. Skowronski, A. Garcia-Tabares Valdivieso, A. Wegscheider (CERN, Geneva, Switzerland)

Abstract

So far, the LHC has operated without any dedicated commissioning of the nonlinear optics at top energy. As β^* is reduced however, the impact of nonlinear errors in experimental insertions may become sizable. Below $\beta^* = 0.8\,\mathrm{m}$, and in particular with possible LHC configurations approaching $0.3\,\mathrm{m}$, an operational impact from uncompensated nonlinear errors in the IRs is to be expected. Notably the contribution of normal octupole errors in IR1 and IR5 to the tune footprint becomes comparable to that created by the Landau octupoles, with implications for the performance of instrumentation and Landau damping of instabilities. In the HL-LHC compensation of IR-nonlinear sources may become a critical issue, with feed-down from IR-sextupole errors having the potential to generate substantial linear optics perturbations. This effect will require an evolution of the linear optics commissioning strategy in the LHC and HL-LHC. Current understanding of the impact of these errors and our ability to correct them will be reported. Nonlinear optics commissioning activities undertaken elsewhere in the machine cycle will also be introduced.

IR OCTUPOLE COMPENSATION

Normal octupole fields create an amplitude dependent tune spread, or tune footprint, within a bunch. For damping of instabilities in the LHC it is generally desired to introduce such a tune spread in a well controlled manner using the Landau octupole magnets located in the LHC arcs, however any octupole source present in the ring will contribute (discussion here is restricted to octupoles which dominate the tune spread for the configurations being considered, however feed-down from higher-order multipoles and feed-up from lower orders will in principle also apply).

The shape and size of the tune footprint may be quantified by its amplitude detuning coefficients. These are first and higher-order terms in a Taylor expansion describing the tune as a function of the action coordinates ($J_{x,y}$, where $x = \sqrt{2\beta_x J_x}\cos\phi_x$). At top energy amplitude detuning can be measured directly using the AC-dipole [1]. Figure 1 shows the amplitude detuning measured at $\beta^* = 0.4\,\mathrm{m}$ during 2016 commissioning. Also shown is the detuning predicted by sixty seeds of LHC magnetic errors.

The measured amplitude detuning is $\sim 2/3$ of what is expected from the LHC magnetic model. This discrepancy precludes simple application of corrections calculated directly from the magnetic model. Correction is desired however, since in-spite of being smaller than expected the measured detuning is still $\sim 1/3$ of that generated by the Landau octupoles in 2016. As linear optics in the IP is squeezed further, the contribution of IR octupole errors to the amplitude detuning increases with $\sim (1/\beta^*)^2$. This is illustrated for the detuning coefficients in Fig. 2, which are quoted in terms of equivalent Landau octupole currents required to generate the same value of the detuning coefficient as due to the IR octupoles.

The impact of normal octupole errors in experimental insertions on tune spread is not a small effect, and can have several operational impacts. Since 2012 it has been observed that online measurement of linear coupling using the LHC BBQ could not be trusted with strongly powered Landau octupoles present in the machine [2, 3]. This is the result of an increased noise floor in the frequency spectrum due to larger tune spread with Landau octupoles powered. At low-β^* however, IR octupole errors mean the LHC operates in a comparable regime regime even with Landau octupoles powered off. Below $\sim 0.8\,\mathrm{m}$ therefore the online BBQ measurement of linear coupling should not be trusted.

During operation for luminosity production the LHC operates with strong Landau octupoles. The settings of these magnets are generally constant during the β^* squeeze, and being located in the arcs the tune spread they generate is effectively unchanged throughout a nominal squeeze. The detuning generated by IR octupole errors, which as seen in Fig. 2 changes significantly during the squeeze, sums with the contribution from the Landau octupoles. Since the pattern of detuning generated in the IRs can differ quite significantly from that conventionally applied with the MO, this leads to considerable distortion of the tune footprint as the squeeze progresses. This is illustrated in Fig. 3 which shows the tune footprint obtained from effective models of detuning measurements, with Landau octupoles powered as applied during 2016 operation. Grey regions show the footprint expected in the absence of the IR contribution, red regions show the expected footprint in the real LHC if IR octupole errors are left uncompensated.

The distortion of tune footprint shown in Fig. 3 at small β^* is substantial. Due to self cancellation of the IR contribution the detuning cross term is largely unaffected. Detuning of Q_y with J_y features a cancellation between the IR and Landau octupole contributions. In contrast detuning of Q_x with J_x is significantly enhanced. By $0.33\,\mathrm{m}$ the footprint in the machine will bear little relation to that desired through application of the MO. Such a distortion of the tune spread within a bunch will impact the stability of the LHC beams. Figure 4 shows the stability diagram calculated from the expected tune spread at $\beta^* = 0.33\,\mathrm{m}$. A significant reduction to stability is seen in the vertical plane,

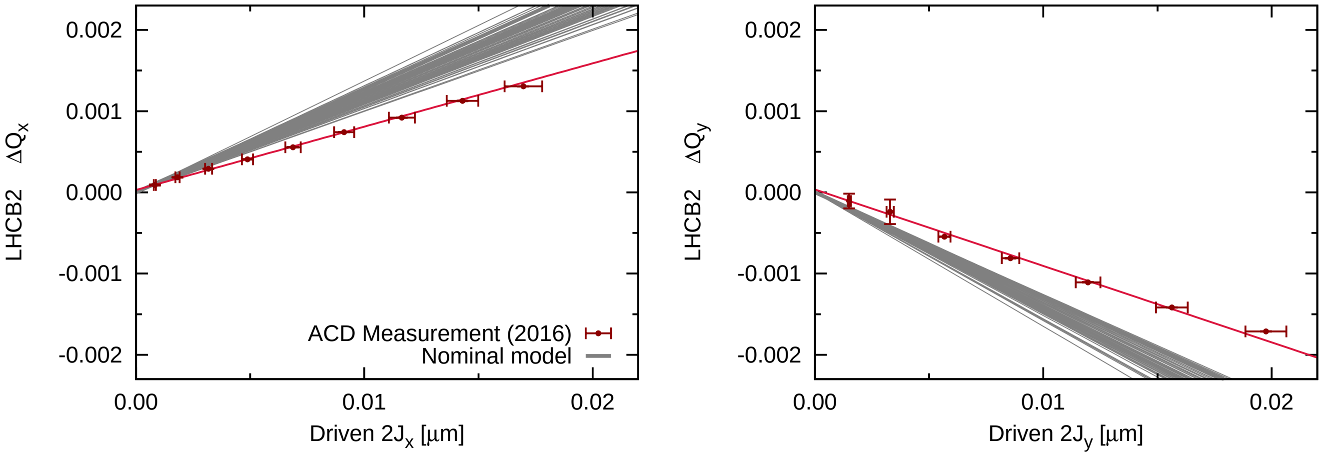

Figure 1: Measured amplitude detuning at $0.4\,\mathrm{m}$ with Landau octupoles powered off.

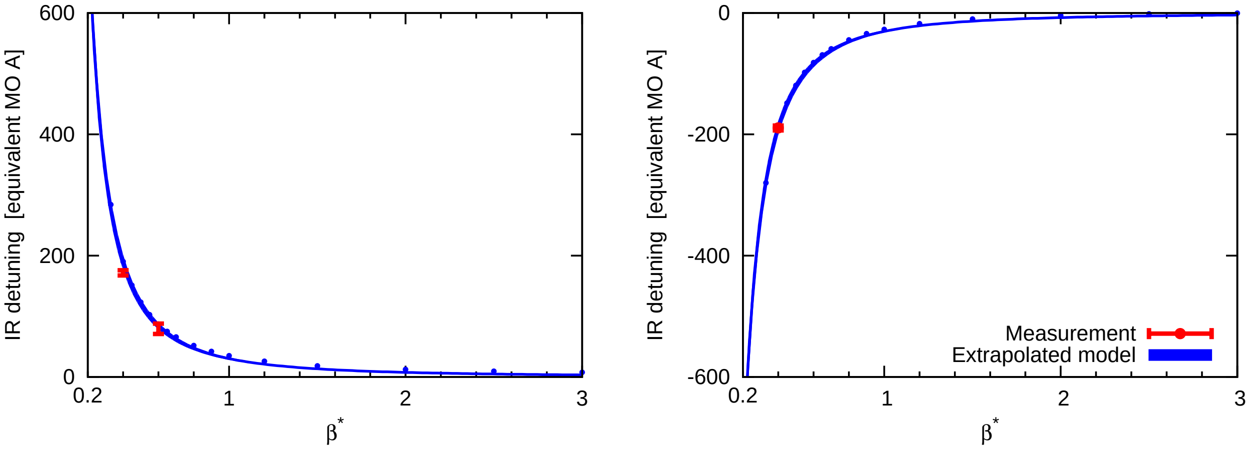

Figure 2: Extrapolated amplitude detuning due to normal octupole errors in IR1 and IR5, expressed in equivalent powering of the Landau octupoles. Extrapolation is based on effective models which reproduce the observed detuning at $0.4\,\mathrm{m}$ and $0.6\,\mathrm{m}$. The maximum powering of the Landau octupoles is $570\,\mathrm{A}$.

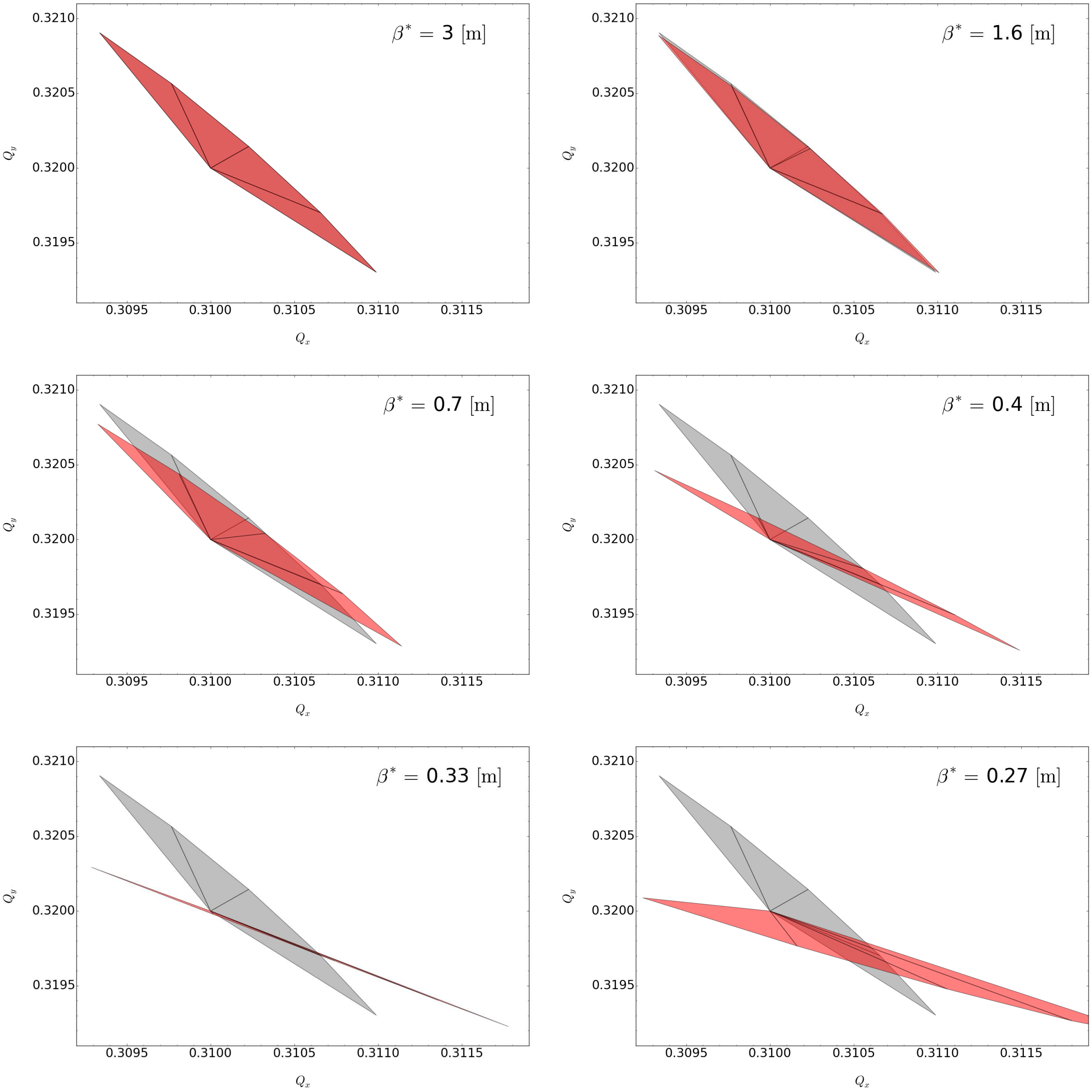

Figure 3: Distortion of tune footprint through the β^* squeeze. Plotted footprints are defined by first-order detuning coefficients obtained via simulation with PTC_NORMAL. The model used consists of an effect model of the normal octupole errors in IR1 and IR5, which reproduces the observed detuning at $\beta^* = 0.4\,\mathrm{m}$, together with Landau octupoles powered as per operation for Luminosity production in late 2016. Grey regions show the footprint expected in the absence of the IR contribution, red regions show the expected footprint in the real LHC if IR octupole errors are left uncompensated.

while the horizontal increased. The predicted change to stability threshold implied by Fig. 4 is unlikely to be a critical challenge to operation at this stage, however it may require an increase to minimum Landau octupole powering. At some β^* however, perhaps in the HL-LHC, it can be expected that the Landau octupoles will run out of strength to generate the tune spread required for the damping of instabilities in the presence of the IR octupole contribution. More generally the variation of the tune spread through the squeeze significantly complicates any attempt to understand and compensate for instabilities in the beam motion. For these reasons implementation of local corrections for IR octupole errors is now becoming a priority from the optics commissioning perspective.

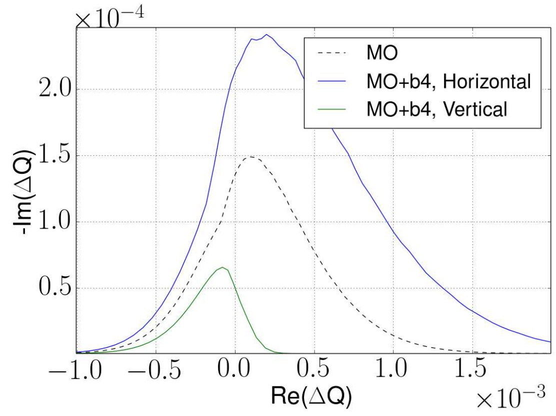

Figure 4: Simulated stability diagram of the LHC at $\beta^* = 0.33\,\mathrm{m}$, with and without the IR octupole detuning contribution.

Local correction of the IR octupole errors can in principle be performed using dedicated b_4 correctors located on the left and right sides of the experimental IRs. As discussed previously however, straightforward correction based upon the magnetic measurements is not possible due to the observed discrepancy with the beam-based measurements (Fig. 1). Amplitude detuning coefficients relate directly to the octupole Hamiltonian terms it is desired to correct, and given the small phase advance over the experimental IRs locally correcting the contribution of each IP to the detuning coefficients should also minimize the resonance driving terms generally. Amplitude detuning however is a global observable and cannot distinguish between the contributions of IR1 and IR5, which together dominate the observed detuning.

To assess locally the octupole errors in the insertions, feed-down to tune was measured as a function of crossing angle in each IP individually. It was found that the second order feed-down to tune in IR1 agreed well with predictions based upon magnetic measurements. This is shown in Fig 5. In contrast the IR5 observations did not agree, and showed a notably reduced second order feed-down relative to expectation. The feed-down measurements alone are too under-constrained to facilitate an understanding of the observed discrepancies or for straightforward calculation of octupole corrections. By validating the magnetic model of normal octupole errors in IR1 however, it allows the contribution of IR1 and IR5 to the amplitude detuning to be distinguished. Corrections for the normal octupole errors were therefore determined by applying the nominal b_4 in IR1 (as calculated from the validated magnetic model) then minimizing the residual detuning with correctors in IR5. The success of the correction was then validated by measuring directly the f'_{4000} resonance driving term (which contributes to the $4Q_x$ resonance) before and after application of the corrections. Figure 6 shows that application of corrections in IR1 and IR5 both served to compensate the octupole resonances in the accelerator.

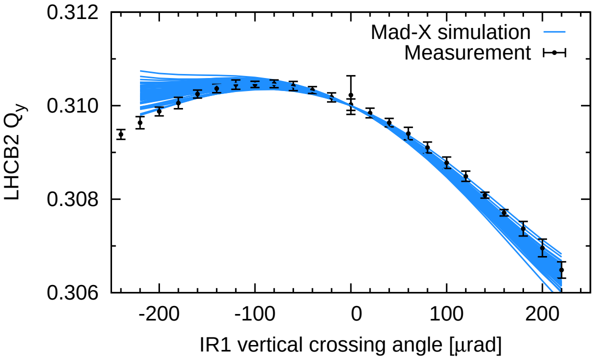

Figure 5: Measured and modelled feed-down to Q_y at $\beta^* = 0.4\,\mathrm{m}$, as a function of a vertical crossing angle orbit bump applied through IR1. Simulated predictions for the sixty wise seeds are shown in blue. An effective model for the skew sextupole errors has been utilized to compensate for a discrepancy in the linear part of the feed-down.

One of the key advantages to correcting IR-octupole errors locally is that the corrections are approximately independent of β^*. The IR1 correction applied to minimize detuning at $0.4\,\mathrm{m}$ was also observed during 2012 to compensate second-order feed-down to tune as a function of crossing angle at $0.6\,\mathrm{m}$ [4]. More significantly when lifetime challenges were encountered during an ATS MD [5] at $\beta^* = 0.14\,\mathrm{m}$ application of the b_4 correction determined at $0.4\,\mathrm{m}$ was observed to give a significant improvement to beam lifetime. This is illustrated in Fig. 7, which shows the fractional intensity change calculated from two minutes prior to application of the IR octupole correction (red), compared to the fractional intensity change calculated from the end of the b_4 correction trim. Data during the time the correction was being applied is excluded due to transient losses generated by tune feed-down.

The studies of IR octupole correction performed during 2016 commissioning and MD time have validated our ability to compensate IR octupole errors in the LHC. For the reasons outlined above it is desired to implement these corrections operationally in 2017. The corrections have been consistent between 2012 and 2016, and shown to be valid over a wide range of β^*. Commissioning of this aspect

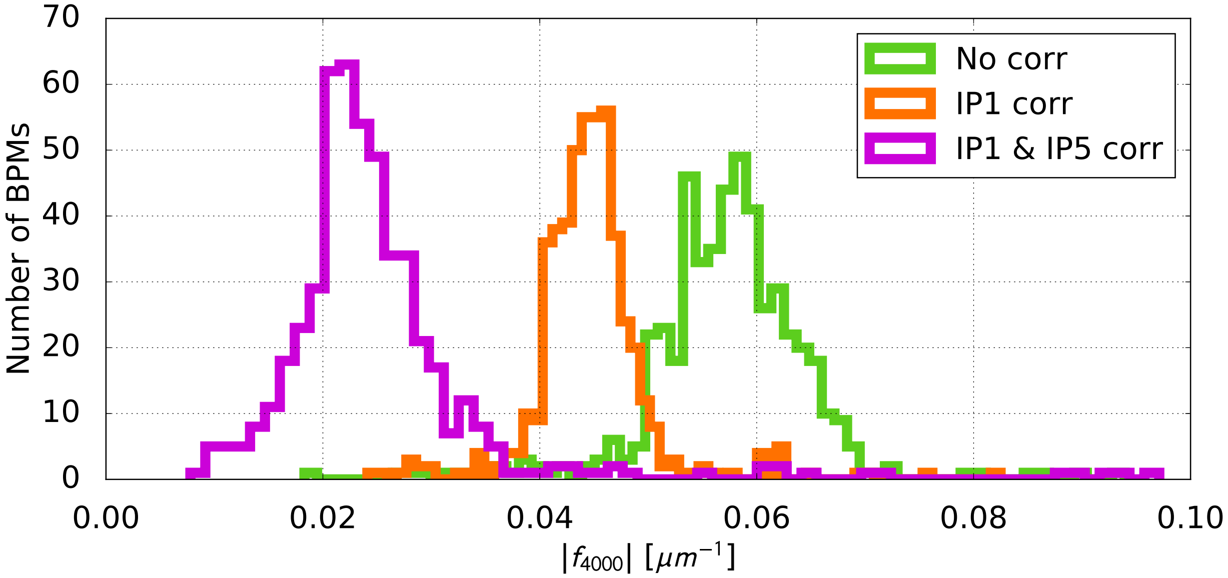

Figure 6: Histograms of the f_{4000} resonance driving term measured at the location of ~ 500 LHC BPMs. Measurements are shown without correction for normal octupole errors in the experimental insertions, with only corrections in IR1 applied, and with corrections in IR5.

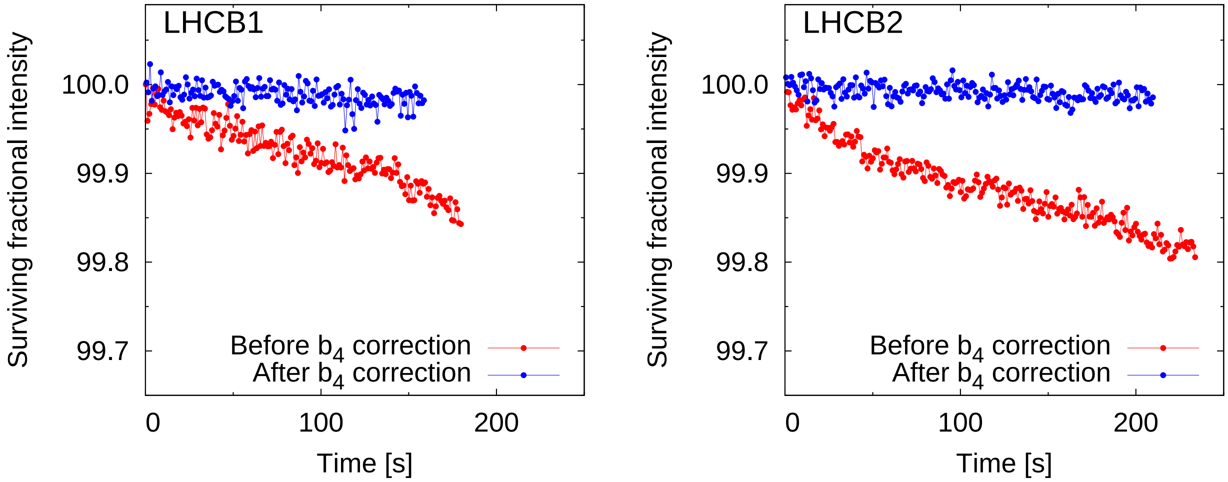

Figure 7: Surviving fractional intensity determined from LHC BCT data. The fractional intensity is calculated from a time 2 minutes prior to application of the IR octupole correction (red), and for two minutes from the time the correction trim completed. Data while the trim was taking place is excluded due to transient losses generated by tune feed-down.

of the nonlinear optics should therefore be straightforward, requiring only $\sim 1/2$ shift for re-validation of the b_4 correction tested in 2016.

IR SEXTUPOLE IMPACT

Normal octupoles are not the only errors in experimental insertions which are of concern in regard to beam optics. During operation for luminosity production the LHC and HL-LHC will operate with significant crossing schemes applied. Due to the offset of the beams through IR magnets however, the nonlinear errors will feed-down to generate linear optics perturbations. Given the small β^*, optics errors in the HL-LHC have the potential to pose serious operational challenges. Figure 8 shows histograms of simulated beta-beating in the HL-LHC at $\beta^* = 0.15\,\mathrm{m}$ due to feed-down from normal and skew sextupole errors for a $295\,\mu\mathrm{rad}$ crossing scheme. Simulations were performed over sixty seeds of the target error tables for the HL-LHC. The peak β-beating around the HL-LHC ring is shown in blue, and the β^* imbalance between ATLAS and CMS is shown in red.

In several of the seeds considered IR-sextupole feed-down alone generated a β-beat which exceeds safe limits for machine operation. A significant number of seeds also fail to provide sufficient margin in the linear optics quality to accommodate residuals from the linear optics commissioning or β-beating from beam-beam within machine protection limits. Finally the β^* imbalance between ATLAS and CMS is intolerably high in the majority of seeds considered. Correction of IR-sextupole errors is likely therefore to be an operational issue in the HL-LHC.

Measurements of beta-beating in the LHC in 2016 imply a peak beta-beat from IR feed-down at about the $3\,\%$ level [6], however measurements were not performed concurrently and may therefore include a contribution from the drift of β-beating with time. The $3\,\%$ figure is of a comparable magnitude to the β^* imbalance obtained in simulation with effective models of the sextupole errors, which reproduce measurements of tune feed-down as a function of crossing angle at $0.4\,\mathrm{m}$. While not a concern in regard to machine protection in the LHC, such an imbalance will scale linearly with $\sim 1/\beta^*$ and is thus a key limitation to achieving the desired optics quality in the LHC. Further, given the significant challenge IR feed-down may pose to optics commissioning in the HL-LHC, it will be important for the optics team to gain experience commissioning for b_3 and a_3 errors in the LHC before compensation becomes a machine protection issue.

Initially optics commissioning should proceed as normal, with local and global corrections determined for a flat orbit. As the IR-sextupole correction does not currently represent a machine protection issue, commissioning of the nonlinear optics may then proceed in parallel with other commissioning tasks. Feed-down to tune and coupling will be measured as a function of the crossing scheme, and where beam-based and magnetic measurements agree the nominal corrections determined from the magnetic model can be applied [4]. Where magnetic measurements are inconsistent with observations of the machine, beam-based corrections can be performed by minimizing the tune shift with crossing angle using dedicated correctors in the IRs. In simulation this is shown to reduce beat-beating. Linear optics quality can then be rechecked with crossing angles applied. If necessary additional corrections to the quadrupole magnets can be applied to optimize the linear optics quality with the crossing scheme present in the machine. Nonlinear optics commissioning would therefore require two shifts: one to perform initial measurements of the sextupole errors (in conjunction with validation of the normal octupole corrections), and one to implement the sextupole correction and perform final linear optics checks.

CHROMATIC COUPLING

Chromatic coupling is the first-order change of $|C^-|$ with $\frac{\Delta p}{p}$. It is generated by skew sextupoles in horizontally dispersive regions, and normal sextupoles in regions of vertical dispersion, with the former being the dominant source. It can be quantified by measuring the change of the f_{1001} resonance driving term as a function of relative momentum offset with AC-dipole kicks. Consequently it can be measured for free when measurements of normalized dispersion are performed during linear optics commissioning.

Correction of the chromatic coupling using skew sextupole correctors in the LHC arcs was demonstrated during dedicated machine development tests in Run 1 [7]. An example of a successful correction at $4\,\mathrm{TeV}$ in 2012 is shown in Fig. 9. Corrections were also calculated in 2015, but compensation of chromatic coupling has never been implemented operationally. Since correction should allow for an improved control of linear coupling with a negligible commissioning overhead, it is desired to incorporate correction of chromatic coupling into the standard suite of optics commissioning activities in 2017.

NONLINEAR DYNAMICS AT INJECTION

At injection in the LHC, octupole and decapole errors in the main dipoles are supposed to be compensated via octupole and decapole spool piece corrector magnets mounted on the ends of every second dipole. Measurements of amplitude detuning and nonlinear chromaticity at $450\,\mathrm{GeV}$ during Run 1 revealed normal octupole sources in the arcs approximately an order of magnitude larger than expected [9, 8]. This has since been explained through hysteresis effects of the octupole spool pieces in combination with an unexpected influence of the decapole spools on the octupole fields [8, 12]. The decapole correction was also found to be a factor ~ 2 stronger than required to compensate the decapole errors, leading to substantially larger third-order chromaticity than expected. The source of the decapole discrepancy remains unknown.

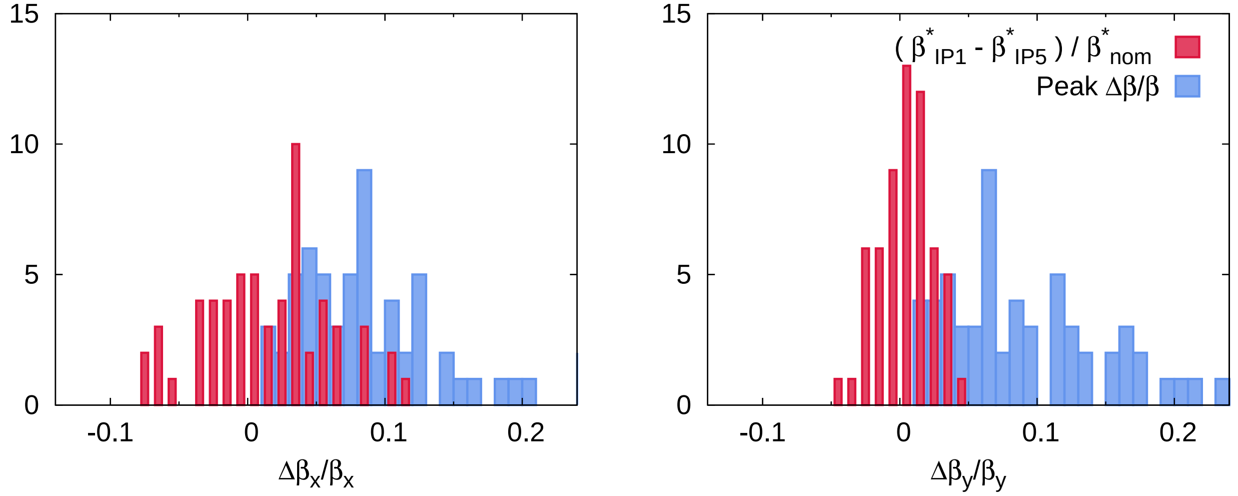

Figure 8: Simulated β-beat due to IR sextupole feed-down in sixty seeds of the HL-LHC error tables at $\beta^* = 0.15\,\mathrm{m}$, $295\,\mu\mathrm{rad}$.

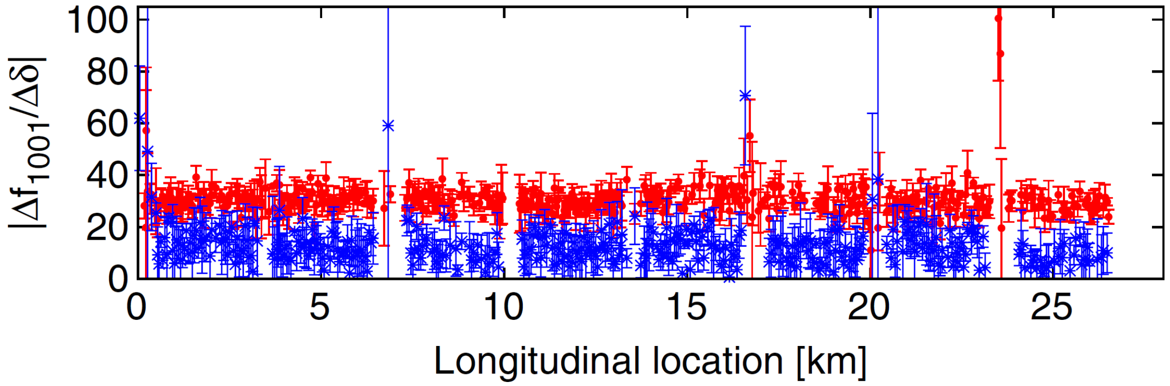

Figure 9: Change of the f_{1001} linear coupling resonance driving term with relative momentum offset, as measured in the LHC BPMs, before (red) and after (blue) correction of chromatic coupling using skew sextupole correctors in the arcs.

Annual measurements of second and third order chromaticity have demonstrated the situation at injection to be extremely stable. Figure 10 compares the nonlinear chromaticity measured in 2011 to that measured in 2015.

Beam-based minimization of the nonlinear chromaticity using the octupole and decapole spool pieces was tested in MD during Run 1 [11]. It was shown to also improve amplitude detuning, dynamic aperture, and the decoherence of kicked beams [10]. Figure 11 shows an example of the decoherence of kicked beams before and after application of the beam-based octupole and decapole corrections. During Run 2 beam-based correction of the nonlinear chromaticity at injection has been implemented in conjunction with linear optics commissioning [12].

The above discussion concerns the situation at injection with depowered Landau octupoles. During regular operation the Landau octupoles are powered. In 2016 there was a substantial increase in their strength applied at injection, leading to some concerns over the impact on dynamic aperture.

In 2012 Landau octupoles were powered $\sim$ 6 times

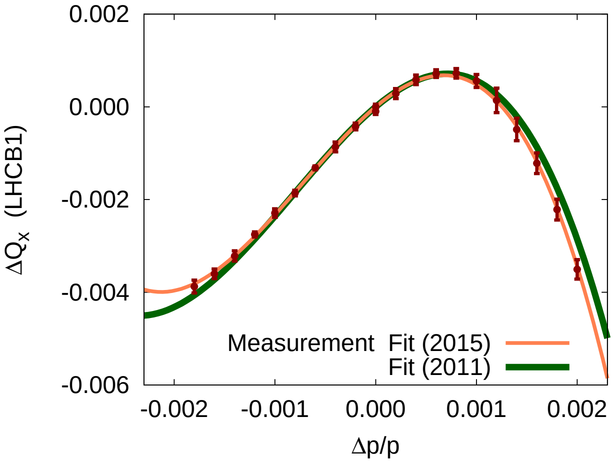

Figure 10: Tune vs relative momentum offset in the LHC at injection during 2011 and 2015.

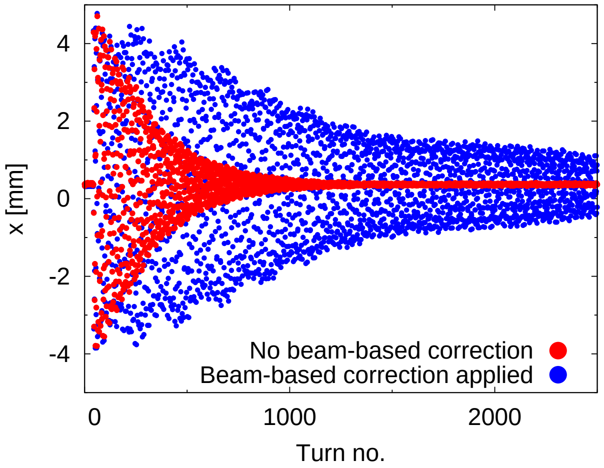

Figure 11: Decoherence of kicked LHC beams at injection, before and after application of beam-based corrections for the nonlinear chromaticity.

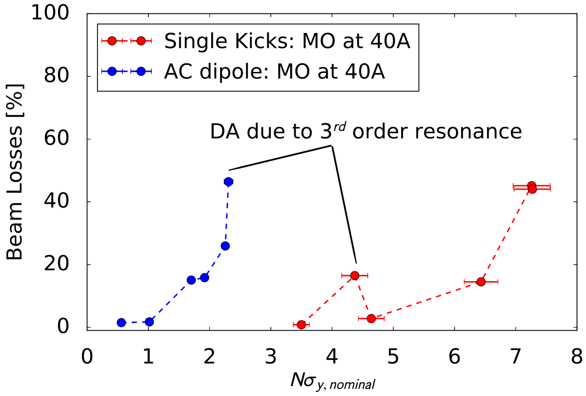

Figure 12: Fractional intensity loss 10^5 turns after application of AC-dipole and single kicks at injection.

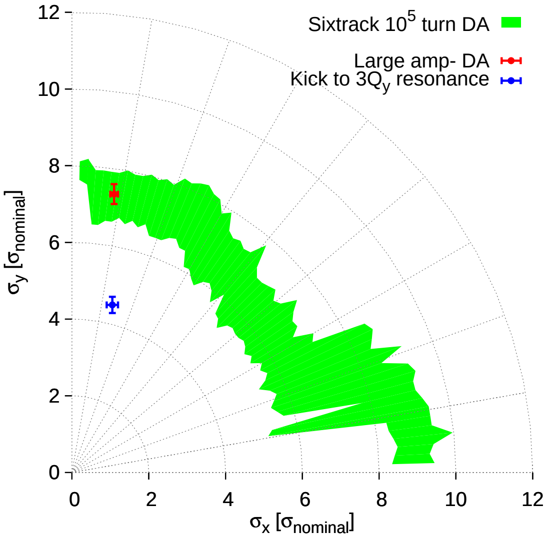

Figure 13: Comparison of 10^5 turn DA simulations in SIXTRACK, to single-kick measurements performed in the LHC at injection.

weaker than in 2016. In this case the single particle dynamic aperture (for $\sim 3 \times 10^5\,\mathrm{turns}$) was limited by the third and fourth order resonances, reached at $\sim 9\,\sigma_{\mathrm{nominal}}$ [10]. In 2016 DA was measured at injection using both AC-dipole and single kicks during MD. The short term DA with AC-dipole was again limited at the third order resonance, around $\sim 2\,\sigma_{\mathrm{nominal}}$. This is consistent with the expected change in detuning relative to 2012 due to increased octupole powering and the effect of the driven oscillation [1]. Single kicks encountered the third order resonance at $\sim 4\,\sigma_{\mathrm{nominal}}$, consistent with the AC-dipole measurement. Unlike 2012 however only modest losses were observed. It was possible to kick the beam beyond the third order resonance, reaching an ultimate DA limit at $\sim 7\,\sigma_{\mathrm{nominal}}$. Figure 12 shows the fractional intensity loss after $1 \times 10^5\,\mathrm{turns}$ for the applied kicks during the 2016 dynamic aperture MD. Figure 13 compares the measured DA to the predicted DA over the same time-scale in SIXTRACK. It is seen that the simulated DA agrees well with the DA limit observed beyond the third order resonance. Losses at the third order resonance were not observed in these SIXTRACK simulation however, potentially implying some missing sources in the model. Still, while DA has clearly been reduced relative to 2012, with the $3Q_y$ resonance now being reached at $4\,\sigma_{\mathrm{nominal}}$ as opposed to $9\,\sigma_{\mathrm{nominal}}$, the situation in terms of dynamic aperture does not appear to be critical in-spite of the dramatically increased Landau octupole powering in 2016.

CONCLUSION

As β^* is reduced in the LHC, the contribution of normal octupole errors in experimental insertions to the tune footprint becomes an operational concern. Their influence is expected to be detrimental to the performance of beam instrumentation, and distortion of the footprint through the squeeze has a negative influence on the damping of instabilities. Correction of IR-octupole errors was achieved during 2016 through a combination of feed-down and amplitude detuning based studies. The positive effects of the correction have been validated through direct observation of octupole resonances and beam-lifetime. It is desired to incorporate this correction operationally in 2017.

Sextupole errors in experimental IRs also become a concern at small β^*, as feed-down from these errors has the potential to generate linear optics perturbations. In the HL-LHC compensation of these errors is a concern in regard to both machine protection and the luminosity imbalance between the ATLAS and CMS experiments. At this stage, correction of IR-sextupole errors is not believed to be a critical issue in the LHC. Given the considerable challenges facing optics commissioning in the HL-LHC however, it is desired to incorporate these effects into the LHC optics commissioning strategy with a view to gaining the experience necessary to ensure successful operation after the high-luminosity upgrade.

It is also desired to incorporate correction of chromatic coupling operationally in the LHC. Control of coupling is essential to the successful operation of the LHC, and compensation of it's momentum dependence can be achieved with a negligible commissioning overhead. At injection beam-based compensation of octupole and decapole errors has been applied operationally since the start of Run 2, again with a negligible overhead. During operation in 2016 Landau octupoles were powered significantly stronger than in previous years, however measurements and simulations do not reveal any critical challenge to such an operational scenario arising from the dynamic aperture.

ACKNOWLEDGMENTS

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