NEW METHODS FOR MEASUREMENT OF NONLINEAR ERRORS IN LHC EXPERIMENTAL IRs AND THEIR APPLICATION IN THE HL-LHC

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Abstract

Studies of nonlinear errors in LHC experimental insertions (IRs) in Run 1 were based upon feed-down to tune and coupling from crossing angle orbit bumps. Useful for validating the magnetic model, this method alone is of limited use to understand discrepancies between magnetic and beam-based measurement. Feed-down from high-order multipoles is also difficult to observe. During Run 2 alternative methods were tested in the LHC. This paper summarizes the results of these tests, and comments on their potential application to the High-Luminoisity LHC upgrade.

INTRODUCTION

Nonlinear (NL) errors in experimental IRs exert significant influence on the beam-dynamics of low-β^* colliders. As the LHC has moved to $0.4\,\mathrm{m}$ operation this has gained operational significance [1, 2, 3]. In the High-Luminosity (HL-) LHC [4] correction of such errors will be an operational necessity [5, 6]. LHC experience demonstrated it is not always possible to calculate corrections from magnetic measurements [7]. To commission corrections for NL-errors in the HL-LHC will require further development of existing and new methods of beam-based study.

FEED-DOWN TO TUNE AND COUPLING

Methods for study of NL-errors based upon feed-down to $Q_{x,y}$ and $|C^-|$ are well established. Feed-down to tune was applied in RHIC experimental IRs [8]. In the LHC feed-down to both $Q_{x,y}$ and $|C^-|$ as a function of the crossing scheme has been used to study errors in low-β IRs [7]. As β^* has reduced however, new limitations on application of this method have developed.

In the LHC operation with active orbit-feed-back (OFB) is not possible while varying orbit bumps. In 2016 large orbit leakage was observed from the CMS (IR5) orbit bump into the ATLAS insertion (IR1). Orbit leakage to the arcs was studied in Run 1 and found to have a negligible impact on feed-down [7], however generation of a substantial crossing-angle like bump in IRs not under investigation can significantly distort measurements. Figure 1 (left) shows leakage to IR1 from an applied bump in IR5, quantified in terms of an effective crossing angle (but not equivalent to the nominal IR1 bump). Orbit leakage can be corrected manually during a crossing angle scan. While increasing significantly the measurement time, the procedure removed unwanted orbit distortion in IR1. Figure 1 (right) shows a substantial impact of orbit leakage on observed feed-down.

Some form of orbit feed-back will be essential for correction of IR-feed-down in the LHC and HL-LHC.
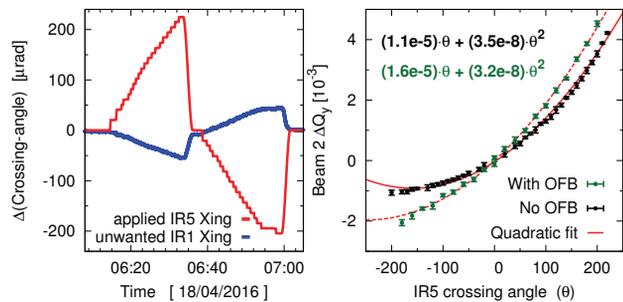

Figure 1: Left: applied crossing angle trim in IR5 (red), and unwanted crossing angle generated at IR1 (blue). Right: orbit leakage compensation altering feed-down.

Until now feed-down to $|C^-|$ in the LHC has been measured via the Base-Band-Tune (BBQ) system, for passive online measurement from residual oscillations. This proved successful during Run 1 [7]. As β^* is reduced, IR-b_4 errors generate substantial tune spread and BBQ performance deteriorates. BBQ based measurement of $|C^-|$ feed-down has in general proved impossible. An alternative measurement is possible using an AC-dipole to excite driven oscillations. Linear coupling resonance driving terms (RDTs) are determined via spectral analysis of turn-by-turn BPM data. Fits to the RDT determine global $|C^-|$. This method is used for linear optics commissioning in the LHC. When performing AC-dipole measurement during a crossing-angle scan, clear shifts to RDTs were observed. The accessible range of crossing angles is reduced by aperture limitations, which cause losses upon AC-dipole kicks, however a sufficient range for study of sextupole and octupole feed-down could still be achieved. $|C^-|$ inferred from RDT shifts is shown in Fig. 2.
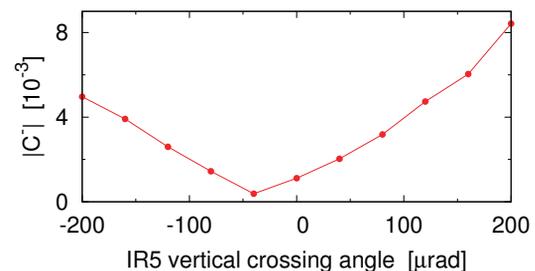

Figure 2: Global $|C^-|$ inferred from RDT measurement with AC-dipole during a crossing-angle scan.

Beam aperture in the HL-LHC will be comparable to the LHC. AC-dipole coupling measurement is thus a viable observable for NL-errors in the LHC and HL-LHC.

Feed-down studies in LHC IRs have so far utilized nominal crossing-angle bumps. This has proved effective for validation of the magnetic model and identification of discrepancies [7]. The method is limited for understanding such discrepancies due to degeneracy of possible source in different regions of the IR. In 2016 first tests were made of asymmetric orbit bumps in LHC IRs, intended to separate contributions coming from opposite sides of the IR. Figure 3 (top) shows an example of such an orbit bump, intended to probe NL-errors on the right side of IR5. Figure 3 (bottom) shows the feed-down to tune in Beam 1 observed for this orbit bump. Correction of orbit leakage was essential, but evidently such asymmetric bumps can be used for the study of sextupole and octupole errors in the LHC. The major limitation on the method came from the maximum available powering on the orbit correctors, which was reached in the course of the scan shown.
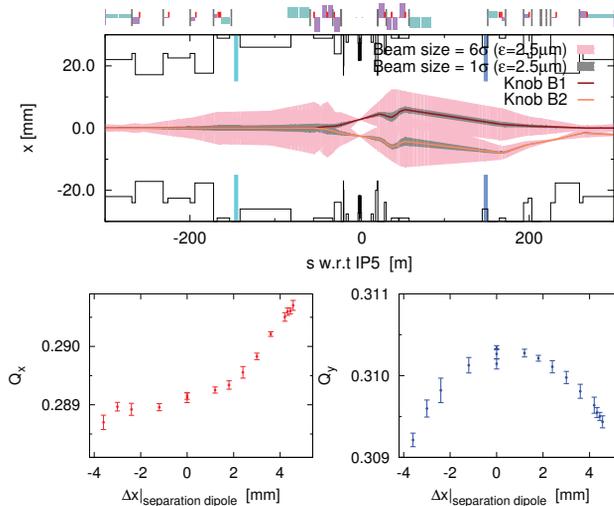

Figure 3: Asymmetric bump to study of right side of IR5 (top). Feed-down measured for this orbit bump (bottom).

AMPLITUDE DETUNING METHODS

In the LHC amplitude detuning at low-β^* is dominated by b_4 errors in IR1 and 5. Detuning generated by these errors was observed to influence Landau damping of instabilities at $0.4\,\mathrm{m}$ [3]. Measurement of detuning coefficients via AC-dipole kicks [9] provides an effective observable of IR-b_4. Figure 4 shows the measured detuning at $0.4\,\mathrm{m}$, compared to simulation. Due to discrepancies with simulation correction for b_4 cannot be calculated directly from magnetic measurements, however beam-based minimization of IR-b_4 tune spread is planned for 2017 LHC commissioning. In the HL-LHC amplitude detuning from b_4 errors can be significantly increased. Figure 5 show a histogram of the expected HL-LHC detuning. The histogram is over 60 realisations of the HL-LHC target error tables. In most cases detuning increased significantly compared to

the LHC. Direct detuning measurement should be viable in HL-LHC, but correction will become even more critical.
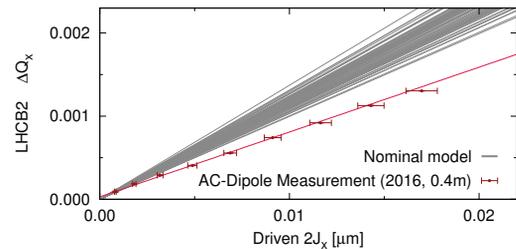

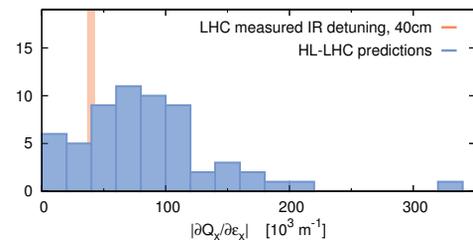Figure 4: Measured and simulated amplitude detuning at $0.4\,\mathrm{m}$ in LHC.

Figure 5: Predicted detuning in HL-LHC at $\beta^* = 0.15\,\mathrm{m}$.

Feed-down to b_4 from b_5, a_5 and b_6, leading to distortion of tune footprint, is also a concern in HL-LHC. During β^* squeeze or crossing-angle leveling footprint change due to feed-down could lead to loss of Landau damping. Figure 6 shows a histogram over HL-LHC target error table realisations, of amplitude detuning generated by decapole feed-down at $\beta^* = 0.15\,\mathrm{m}$ (nominal crossing-scheme). At up to double the level of b_4 detuning in the LHC at $0.4\,\mathrm{m}$ (which is already seen to influence Landau damping) there is a clear motivation for decapole compensation.
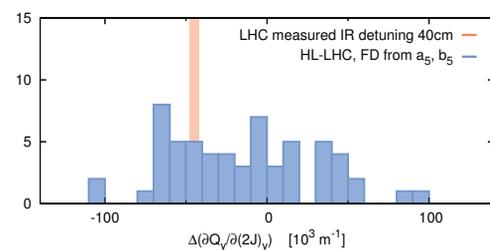

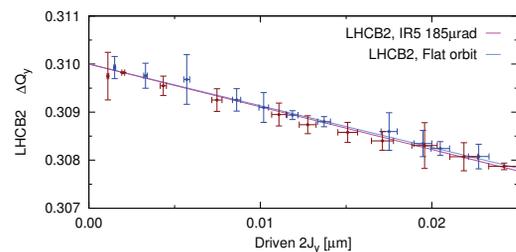Figure 6: Predicted b_5,a_5 feed-down in HL-LHC at $0.15\,\mathrm{m}$.

Figure 7: Measured LHC amplitude detuning with and without crossing-scheme applied at $0.4\,\mathrm{m}$.

05 Beam Dynamics and Electromagnetic Fields

Normally detuning measurement at $6.5\,\mathrm{TeV}$ in the LHC is performed with flat orbit. Studies in 2016 tested measurement with crossing-angle applied. Available aperture for AC-dipole kicks was reduced with the crossing-scheme applied, but large direct detuning terms could be measured easily. Figure 7 shows a measurement with and without IR5 crossing-angle applied. No feed-down from higher-order errors was observed. Measurement of small cross-term detuning coefficients was limited by tune stability between kicks, due to the smaller amplitude range (and hence smaller tune shifts) measured. A resolution of $\sim 10 \times 10^3\,\mathrm{m}^{-1}$ was reliably obtained for detuning shifts. Comparing to Fig. 6, study of decapole errors via feed-down to b_4 should be viable in HL-LHC.

RESONANCE DRIVING TERMS

RDTs provide a direct observable for NL-errors. LHC measurements at $0.4\,\mathrm{m}$ have demonstrated the ability to measure a broad range of RDTs corresponding to sextupole and octupole resonances (Fig. 8). In 2016 it was also demonstrated that appropriate choice of AC-dipole working point could enhance RDTs for specific resonances, allowing improved measurement. Enhancement of f_{4000} (an RDT driving the $4Q_x$ resonance) going from nominal $Q_{x,y}$ (0.28, 0.31) to a working point closer to $4Q_x$ (0.27, 0.31) is shown in Fig. 9. For the HL-LHC it will be of interest to study enhancement of decapole and dodecapole RDTs, which have not yet been observed in the LHC.
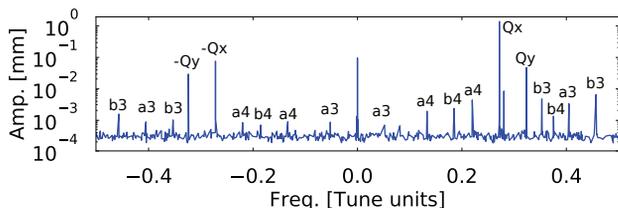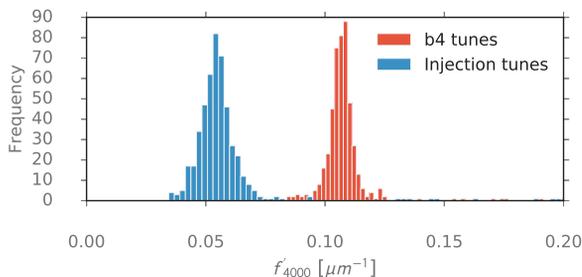

Figure 8: Measured tune spectrum in LHC at $0.4\,\mathrm{m}$

Figure 9: Enhancement of b_4 RDT by working point.

DYNAMIC APERTURE (DA)

Dodecapolar errors are expected to have a significant impact on lifetime in the HL-LHC, and direct DA measurement may be viable for such high-order errors. DA measurement using single kicks is not viable, due to lack

of kicker strength and the destructive nature of the measurement. A possible alternative is measurement via slow blow-up with the transverse damper. Intensity can then be monitored as a function of corrector powering to determine DA [10]. The technique has been demonstrated at injection [11, 12]. First tests at $6.5\,\mathrm{TeV}$ were performed in 2016 using IR-b_6 correctors to intentionally change DA. Figure 10 shows a clear impact of a b_6 trim on lifetime and intensity. Figure 11 shows DA (in σ_{beam}) inferred from measured losses. A clear change to DA is observed with b_6 corrector strength. These studies provide a first indication that direct DA measurement may be a viable option for dodecapole compensation in the LHC and HL-LHC. Studies of short-term DA by AC-dipole kicks also delivered promising results [13, 14].
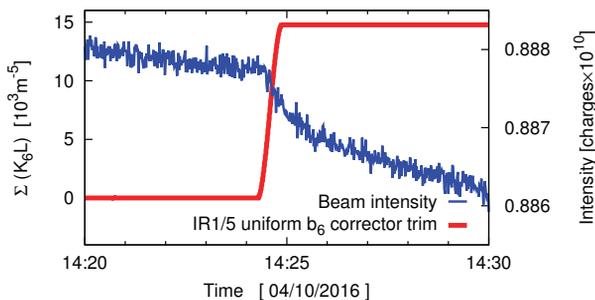

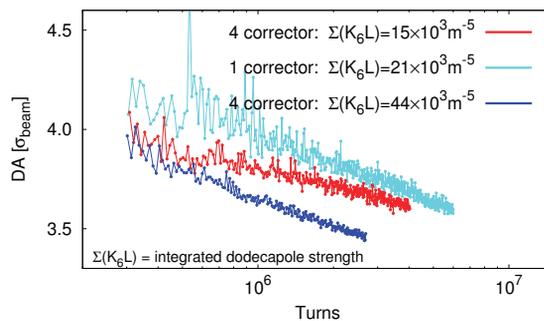Figure 10: Beam intensity following a trim of b_6 correctors.

Figure 11: Measured DA inferred from beam loss.

CONCLUSIONS

Correction of nonlinear errors in low-β IRs will be vital for successful operation of the HL-LHC. In 2016 refinements to existing methods based upon feed-down to $Q_{x,y}$ and $|C^-|$ were demonstrated to improve the ability to study such errors in the LHC. New methods based upon RDTs, amplitude detuning and direct DA measurement via AC-dipole and slow blow-up were also tested for the first time, with promising results in regard to compensation of high-order errors in the HL-LHC.

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05 Beam Dynamics and Electromagnetic Fields

D02 Non-linear Single Particle Dynamics - Resonances, Tracking, Higher Order, Dynamic Aperture, Code   3157

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