NON-LINEAR ERRORS IN THE EXPERIMENTAL INSERTIONS OF THE LHC

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Abstract

Correction of nonlinear magnetic errors in low-β insertions can be of critical significance for the operation of a collider. This is expected to be of particular relevance to LHC Run II and the HL-LHC upgrade, as well as to future colliders such as the FCC. Current correction strategies for these accelerators have assumed it will be possible to calculate optimized local corrections through the insertions using a magnetic model of the errors. To test this assumption the nonlinear errors in the LHC experimental insertions have been examined via feed-down and amplitude detuning. It will be shown that while in some cases the magnetic measurements provide a sufficient description of the errors, in others large discrepancies exist which will require beam-based correction techniques.

INTRODUCTION

As the LHC progresses to more challenging β^* regimes nonlinear errors in the low-β insertion regions (IRs) will play an increasing role in limiting the performance of the accelerator. In particular a $\sim 5\sigma$ reduction in dynamic aperture is expected in the HL-LHC due to these errors [1]. For this reason dedicated nonlinear correctors are provided in the common-beam regions left and right of the experimental insertions. A schematic of the corrector layout is shown in Fig. 1.

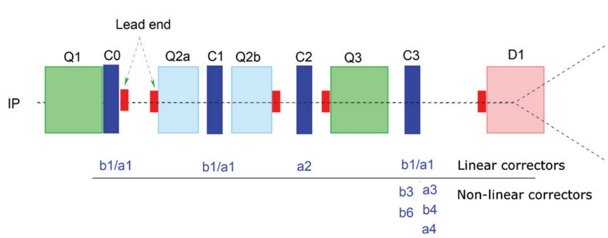

Figure 1: Corrector layout in LHC experimental IRs [2].

Two correction strategies have been considered for the LHC and HL-LHC. The first method compensates magnetic errors in IR elements via local minimization of selected resonance driving terms [2]. The second method is based upon a direct compensation of the transverse map coefficients left and right of the interaction point (IP) [3]. For these strategies to be valid however, an accurate magnetic model of the insertions is required. Magnetic measurements performed on the LHC magnets during construction provide a foundation for such a model, but must be verified and refined through beam-based measurements to ensure the validity of the IR correction scheme.

Strategies for nonlinear correction based upon feed-down to tune have previously been employed around the whole ring in SIS18 and CERN-SPS [4, 5], and in the RHIC experimental insertions [6]. In the RHIC method linear coupling was held constant during the feed-down scan, with correction attempted through minimization of observed tune shifts. At the LHC study of nonlinear multipoles in the IRs has been performed through feed-down to both tune and linear coupling. The focus of the studies in the LHC was also upon testing the magnetic model, rather than any beam-based minimization of the observable symptoms of the nonlinear errors. Table 1 summarizes the feed-down of normal and skew nonlinear multipoles, due to horizontal or vertical displacement from the magnetic axis, generating shifts in tune (ΔQ) and linear coupling ($\Delta|C^-|$).

In Run I such studies were performed in the LHC by varying crossing angle bumps in the IRs, which are intended for prevention of collisions at parasitic crossing points either side of the IP (studies were performed with non-colliding probe bunches). More details of Run I studies may be found in [7, 8]. In 2015 feed-down scans were also performed [9], however new theoretical developments [10] also allowed use of an AC-dipole for measurement of amplitude detuning at top energy, providing an additional measure of normal octupole errors.

MODEL VS MEASUREMENT

Results from beam-based studies were compared to predictions of MAD-X simulations incorporating the best available knowledge of the magnetic errors in the IRs. This allowed for the validation of several components of the LHC magnetic model. Figure 2 shows an excellent agreement between modelled and measured variation of linear coupling with vertical crossing angle in the ALICE IR (IR2), dominated by the b_3 component of the separation dipoles.

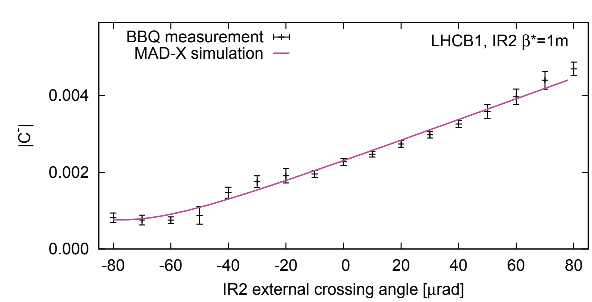

Figure 2: Modelled and measured change of $|C^-|$ with vertical crossing angle in the ALICE IR ($\beta^* = 1$ m).

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Table 1: Feed-down to tune (ΔQ) and coupling ($\Delta|C^-|$) due to horizontal or vertical displacement from the magnetic axis. b_3 is a normal sextupole.

Multipole	b_3	a_3	b_4	a_4	b_5	a_5	b_6	...
Horizontal displacement	ΔQ	$\Delta|C^-|$	ΔQ	$\Delta|C^-|$	ΔQ	$\Delta|C^-|$	ΔQ	...
Vertical displacement	$\Delta|C^-|$	ΔQ	ΔQ	$\Delta|C^-|$	$\Delta|C^-|$	ΔQ	ΔQ	...

Figure 3 shows the variation of measured and simulated feed-down to $|C^-|$ with vertical crossing angle in the ATLAS insertion (IR1). In this case uncertainties on the magnetic measurements are non-negligible. This is reflected in simulation by considering 60 instances of the magnetic errors ('seeds'), distributed according to the uncertainties on the magnetic measurements. The 60 seeds are plotted individually in Fig. 3. Variation of coupling in Fig. 3 is mainly driven by feed-down from b_3 and a_4 errors. Residuals between the measurement and seeds were shown to depend primarily with the b_3 component of the separation dipoles. By considering the 60 seeds in conjunction with the beam-based measurements it was possible to calculate a more refined correction for b_3 in IR1 than would be possible from magnetic measurements alone.

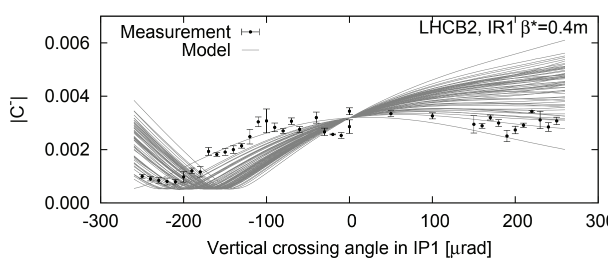

Figure 3: Modelled and measured change of $|C^-|$ with vertical crossing angle in the ATLAS IR ($\beta^* = 0.4$ m).

While some multipoles agreed well between the magnetic and beam-based measurements, others showed substantial discrepancies. Figures 4 and 5 show measured and modelled feed-down to tune versus crossing angle in the ATLAS (IR1) and CMS (IR5) insertions respectively.

Substantial differences are seen between the observed and expected linear variation of the tune (corresponding to a_3 in IR1 and b_3 in IR5). These discrepancies are not understood at present. In IR5 the net quadratic variation of tune (corresponding to b_4) is significantly smaller than predicted, while in IR1 quadratic variation of Q_y (also corresponding to b_4) agrees well with the magnetic model. Discrepancies in the nonlinear variation of Q_x with crossing angle in IR1 could be explained either by a discrepancy in b_4 (generally inconsistent with the Q_y observation) or by a combination of a_5 and b_6.

Figure 6 shows measured and simulated amplitude detuning for the optics configuration in Figs. 4 and 5. First-order amplitude detuning at $\beta^* = 0.4$ m is dominated by b_4 errors in IR1 and IR5. The measured detuning, and hence the net b_4, is half that expected from magnetic measurements.

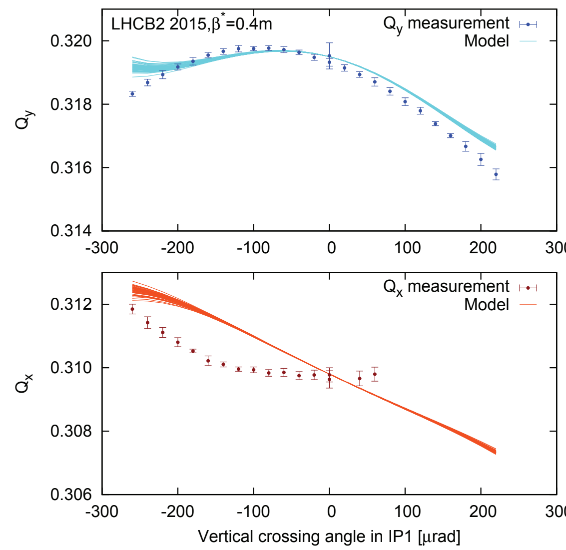

Figure 4: Modelled and measured change of $Q_{x,y}$ with vertical crossing angle in the ATLAS IR ($\beta^* = 0.4$ m).

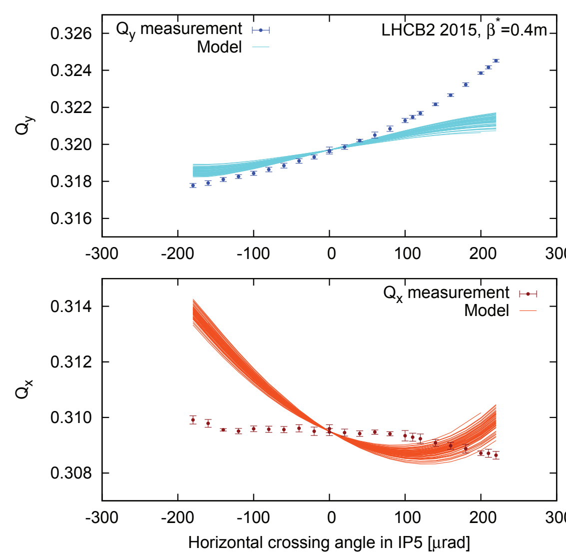

Figure 5: Modelled and measured change of $Q_{x,y}$ with horizontal crossing angle in the CMS IR ($\beta^* = 0.4$ m).

Given the small quadratic tune variation with crossing angle observed in IR5, and the good agreement for Q_y obtained in IR1, these measurements may suggest an octupole error configuration close to the magnetic model in IR1 but substantially smaller than the magnetic measurements in IR5.

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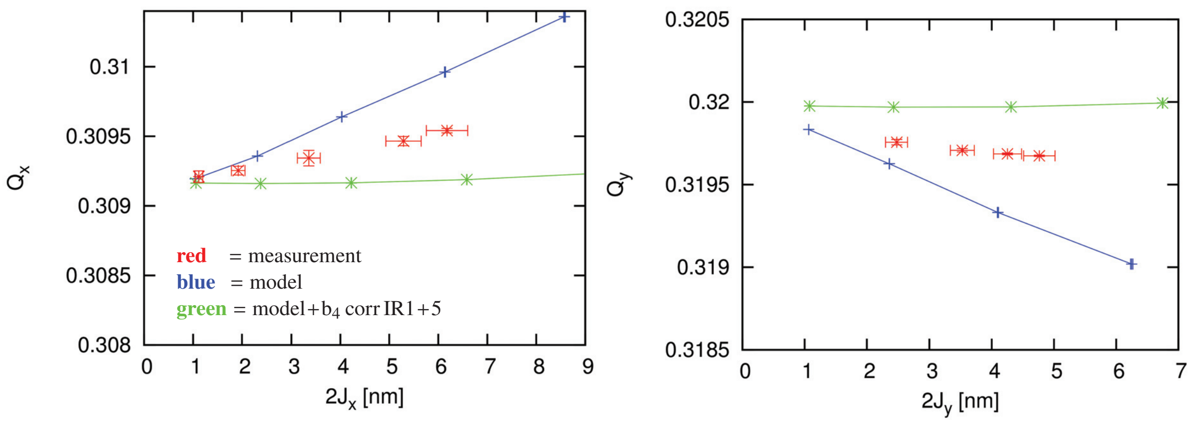

Figure 6: Modelled and measured amplitude detuning ($\beta^*_{\mathrm{IP1,5}} = 0.4\,\mathrm{m}$).

When corrections for b_4 errors in IR1 determined from the magnetic model are applied in simulation detuning with amplitude is reduced by the amount required to correct the observed values in Fig. 6. During Run I correction of b_4 in IR1, based upon the magnetic model, was performed at $\beta^* = 0.6\,\mathrm{m}$ and substantially reduced quadratic variation of tune with crossing angle. Simultaneous correction of amplitude detuning and quadratic tune variation with orbit (which these observations suggest to be the case) would be a strong indication of a good correction as the two observables are not directly related, except through the b_4.

As mentioned, tests of b_4 correction during Run I successfully reduced quadratic tune variation with crossing angle in IR1. However, while the quadratic variation was reduced, in LHC Beam 1 the b_4 correction also introduced a substantial linear tune variation, corresponding to feed-down to a_3 from the correction itself. This is illustrated in Fig. 7 which shows the tune variation before (top) and after (bottom) correction. Lower-order nonlinear errors, introduced by correction of even-higher-order multipoles, may need to be compensated if the nonlinear corrections in the experimental insertions are to prove effective in improving accelerator performance. This further demonstrates the importance of beam-based methods to understand the nonlinear errors, and to test the effectiveness of their correction.

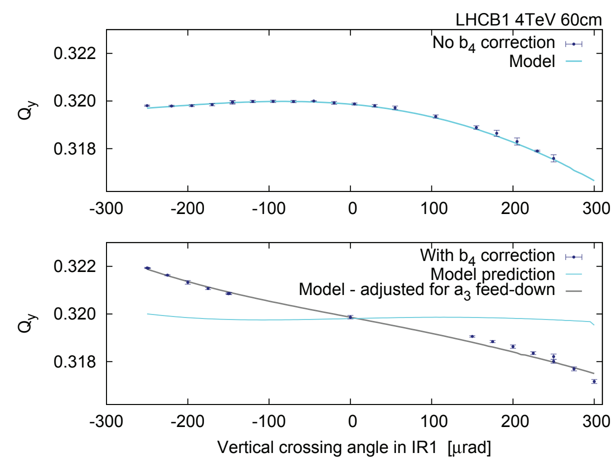

Figure 7: Effect of b_4 correction at $\beta^* = 0.6\,\mathrm{m}$ on Q_y of LHC Beam 1.

CONCLUSIONS

Nonlinear errors in low-β insertions can have a significant impact upon beam-dynamics, and their correction represents a potential avenue of attack towards improving machine performance. In the LHC and HL-LHC it has been assumed that such corrections can be calculated from magnetic measurements performed during construction. While beam-based methods have indeed validated the magnetic model for a number of multipoles, they have also highlighted significant discrepancies between the observed and expected behaviour. Reliance upon magnetic measurements alone will not suffice to ensure proper correction.

Beam-based study using a combination of feed-down and amplitude-detuning observables appears promising for b_4, however in the HL-LHC higher-order multipoles may be a significant factor affecting performance. Various methods for the study of nonlinear errors have been applied at LHC injection, notably dynamic aperture, higher-order amplitude detuning, and resonance driving terms [8,11–14]. Approaching the HL-LHC era application of such techniques at high energy should be explored.

ACKNOWLEDGMENTS

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