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Report from LHC MD 1391: First tests of the variation of amplitude detuning with crossing angle as an observable for high-order errors in low-β^* colliders

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Summary

Nonlinear errors in experimental insertions can pose a significant challenge to the operability of low-β^* colliders. When crossing schemes are applied high-order errors, such as decapole and dodecapole multipole components in triplets and separation dipoles, can feed-down to give a normal octupole perturbation. Such fields may contribute to distortion of the assumed tune footprint, influencing lifetime and the Landau damping of instabilities. Conversely, comparison of amplitude detuning coefficients with and without crossing schemes applied should allow for the beam-based study of such high-order errors. In this note first measurements of amplitude detuning with crossing bumps in the experimental insertions are reported.

Contents

1 Motivation

Increases to delivered luminosity in the LHC are being sought through reduction of β^*. The High-Luminosity upgrade will also involve a considerable reduction to the β functions in the interaction points. As the linear optics at the IPs are more tightly squeezed, β-functions in the triplets and separation dipoles increase. Nonlinear errors in such elements are correspondingly expected to have a larger impact on the accelerator optics.

Normal octupole fields generate an action dependent tune shift ('amplitude detuning'), which contributes to the tune footprint of the accelerator beams. There are three first-order detuning coefficients (where first-order implies a linear variation of the tune with action). $\partial Q_x/\partial(2J_x)$ and $\partial Q_y/\partial(2J_y)$ are referred to as the 'direct' horizontal and vertical detuning coefficients. The 'cross-term' detuning coefficients are always equal by definition: $\partial Q_x/\partial(2J_y) = \partial Q_y/\partial(2J_x)$. This first-order amplitude detuning is generated by normal octupole fields to first-order in the multipole strength.

At large β^* in the LHC the first-order detuning, and hence the form of the tune footprint, is usually dominated by the contribution of the Landau octupoles: normal octupole magnets which intentionally generate amplitude detuning for the damping of instabilities. Located in the arcs, the Landau octupole (MO) contribution to the tune footprint is approximately constant throughout a nominal LHC squeeze. By contrast the contribution to tune footprint from normal octupole fields in experimental insertions scales with $\sim (1/\beta^*)^2$. At low β^* the contribution from nonlinear errors can become significant, leading to cancellation or enhancement of the detuning generated by the MO with potential implications for machine operation.

Amplitude detuning coefficients can be measured using AC-dipole excitation [1] and measurement with flat orbit is now a routine part of LHC commissioning and beam-based study. Measurements of amplitude detuning have shown that tune spread generated by normal octupole errors in the ATLAS and CMS insertions becomes comparable with that generated by the Landau octupoles below $\sim \beta^* = 0.8\,\mathrm{m}$ [2]. This has been shown to have a non-negligible impact on the instability threshold in the LHC [3]. Correction of normal octupole sources in the experimental insertions was demonstrated in 2016 [2, 4], however all studies of amplitude detuning at top energy have so far been performed with a flat orbit. During operation for luminosity production, crossing schemes are applied in the experimental insertions. In the operational scenario therefore, there is the potential for additional contributions to the tune footprint due to feed-down from high-order errors such as normal/skew decapoles and normal dodecapoles. Figure 1 shows predictions for the change to detuning coefficients due to decapole only feed-down in the HL-LHC at $\beta^* = 0.15\,\mathrm{m}$ with a $295\,\mu\mathrm{rad}$ crossing scheme, based on target error tables for the triplets and separation dipoles. 60 seeds of the errors were considered.

In the HL-LHC feed-down from the IR decapole errors alone has the potential to generate as much as double the IR detuning contribution observed from octupole errors in the LHC at $0.4\,\mathrm{m}$. Dodecapole feed-down can further enhance the IR contribution to the tune spread. At this level an operational impact due to feed-down of high-order nonlinear errors in the experimental insertions of the HL-LHC should be expected. Such contributions to the transverse footprint are also of immediate interest in the LHC, where the stability threshold is not completely understood [5].

The objective of this MD was to gain experience measuring amplitude detuning at top energy with a crossing scheme applied, with a view to using methods based on such a measurement for the study of high-order nonlinearities in experimental insertions.

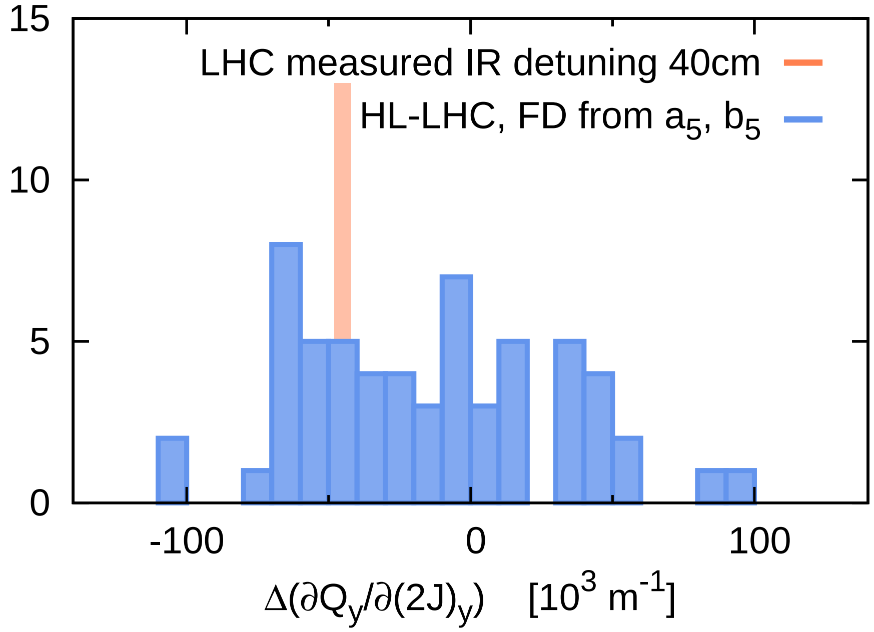

Figure 1: Expected detuning change in the HL-LHC due to decapole feed-down with the nominal crossing scheme at $\beta^* = 0.15\,\mathrm{m}$.

2 Measurement summary

Table 1: Measurement summary

MD #:	1391
FILL #:	5363
Beam Process:	MD → SQUEEZE-6.5TeV-3m-40cm-2016_V1_MD4@1050_[END]
Date:	04/10/2016
Start Time:	11:15
End Time:	12:40
Beams:	1 & 2

Amplitude detuning coefficients were measured firstly with a flat-orbit, then with the nominal crossing angle in IR5 applied. The crossing scheme was only applied in IR5 to differentiate contributions from the various experimental insertions. At the start of the MD coupling was corrected to the $|C^-| < 5 \times 10^{-4}$ level using AC-dipole methods [6]. Several other measurements were performed prior to the beginning of this particular study, therefore coupling quality was rechecked prior to the amplitude detuning measurement. No further correction of linear coupling was required. Injection tunes were used for IR-nonlinear studies during this MD to provide sufficient space in the tune diagram that measurements of the nonlinear optics were unaffected by the coupling resonance. Amplitude detuning measurements were performed in the vertical plane for Beam 1 and Beam 2.

Following completion of the flat-orbit measurement the IR5 crossing angle knob was trimmed to a value of $+185\,\mu\mathrm{rad}$. An orbit correction was applied to limit any feed-down contribution from the arcs and other IPs due to non-closure of the IR5 crossing scheme. Tunes were corrected back to the values used for the flat-orbit measurement ($Q_x = 0.28$, $Q_y = 0.31$). Finally coupling was re-corrected to the $\sim 10^{-4}$ level using the AC-dipole. Amplitude detuning measurements were performed in the vertical plane of Beam 1 and 2. Measurements in the horizontal plane were then performed for Beam 2 only.

As described above, linear coupling during this MD was corrected well below normal operational values. Precise correction of the coupling is essential for detailed measurements of the nonlinear optics, to ensure any change results from feed-down rather than the influence of linear coupling. Studies of amplitude detuning at injection and top energy in the LHC during Run 1 demonstrated that small changes to linear coupling could cause shifts to the detuning coefficients / footprint which are non-negligible on the scale of interest in this MD [1, 7, 8, 9]. Furthermore, amplitude dependent closest-tune-approach [7, 10, 11], an action dependent analogue of the ΔQ_{min} created by linear coupling, is generated through the combination of linear coupling and octupole fields. The effect creates highly nonlinear distortions of the footprint as particles detune towards the difference coupling ($Q_x - Q_y$) stop-band. Since the presented analysis of feed-down from high-order multipoles is based upon shifts in first-order detuning coefficients this effect should be avoided. Maintaining $|C^{-}|$ at the $\sim 10^{-4}$ level ensures linear coupling has a negligible impact on the amplitude detuning shifts studied in this analysis.

Prior to the amplitude detuning measurements a study was performed to examine the influence of natural and driven working point on measurement of resonance driving terms. During this study the emittance of Beam 1 was unintentionally blown-up by the applied AC-dipole kicks. During the amplitude detuning measurement a correspondingly lower kick amplitude could be achieved in Beam 1. As additional studies were planned after completion of the amplitude detuning component of the MD, horizontal detuning measurements were performed only for Beam 2.

3 Results

Figure 2 shows the measured amplitude detuning of LHC Beam 2 for vertical kicks. Fits of the first order detuning terms obtained via orthogonal distance regression are shown. While unperturbed tunes were corrected back to their previous values following application of the IR5 crossing bump, given the LHC BBQ resolution at $40\,\mathrm{cm}$ this was only possible to within $\sim 1\times10^{-3}$. For comparison of the data before and after application of the orbit bump, plotted data has been adjusted to shift the unperturbed tune from the value determined through fitting, to a working point of (0.28,0.31). In simulation tune shifts at the 10^{-3} level had a negligible impact on the detuning coefficients.

Direct (Fig. 2, top) detuning terms were successfully measured with and without the crossing bump applied. The obtained values for the detuning coefficients were consistent with measurements performed earlier in the year, and showed no appreciable feed-down effect upon application of the crossing bump. Cross-term detuning coefficients (Fig. 2, bottom) are significantly smaller than direct terms. There appears to have been a change of trend in the detuning measurement for kicks above $2J_y \sim 0.007\,\mu\mathrm{m}$. This could indicate an entirely plausible tune drift at the 10^{-4} level, or reflect the difficulty measuring natural tune in the undriven plane at small amplitude. Obtaining an accurate measure of cross-term detuning via a first-order fit to this data is unreliable, as was reflected in large values of the $\chi^2_{reduced}$ statisic (up to ~ 4.5) for these fits. While an absolute measurement was not possible, a limit of several thousand m^{-1} can be placed on any potential feed-down from the higher-order errors, which is negligible on the operational scale of the LHC.

The available kick amplitude in the horizontal plane was reduced compared to the vertical measurement. This was due to a reduction of the horizontal aperture upon applying the IR5 (horizontal) crossing angle. Measurement results are shown in Fig 3. Measurement of the direct detuning term was of a high quality in-spite of the smaller amplitude range, however the shift of vertical tune with horizontal amplitude appears to have been comparable with the tune stability between kicks. A linear

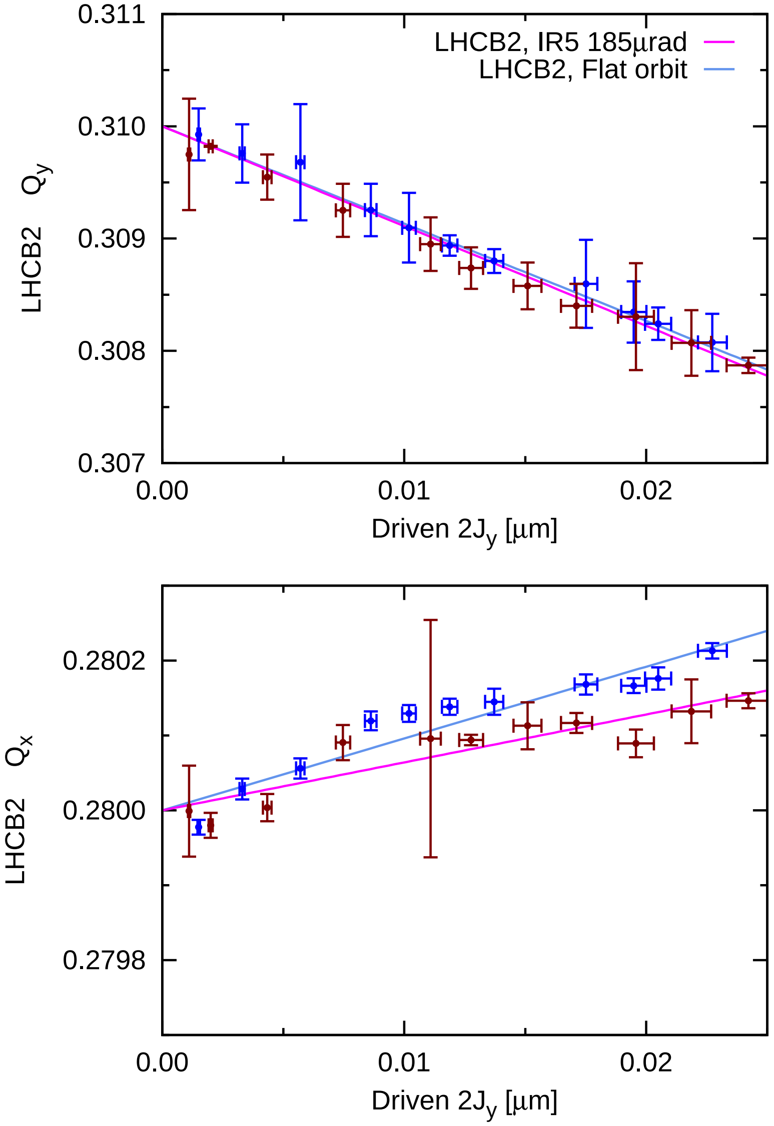

Figure 2: Measured detuning of LHC Beam 2 with vertical amplitude, with and without the IR5 crossing angle applied.

fit to cross-term data yielded $\chi^2_{reduced} >> 1$ reflecting that this data cannot be adequately interpreted in terms of the detuning coefficients. Consequently it has not been included in any further analysis. Values for the horizontal direct term detuning were comparable to those measured during 2016 commissioning.

Measurements of the vertical detuning of Beam 1 were of lower quality than achieved in Beam 2, due to blow-up of the beam during a previous study. A smaller range of actions could be probed and measurement of the natural tune was hampered. Of the 10 kicks performed at flat orbit, good tune measurements were only obtained in 3-4 cases. Figure 4 shows the direct vertical detuning measurements of LHC Beam 1 with and without the IR5 crossing scheme applied. Note the smaller horizontal scale than shown in Fig. 2.

Figure 5 compares the cross-term detuning measured for Beam 1 before and after application of the crossing bump. In this case there appears to have been a change in the sign of the detuning coefficients upon applying the crossing angle. With a total observed tune shift of $\sim\ 2 \times 10^{-4}$ however such measurements of the cross term are at the limit of what we may consider to be a

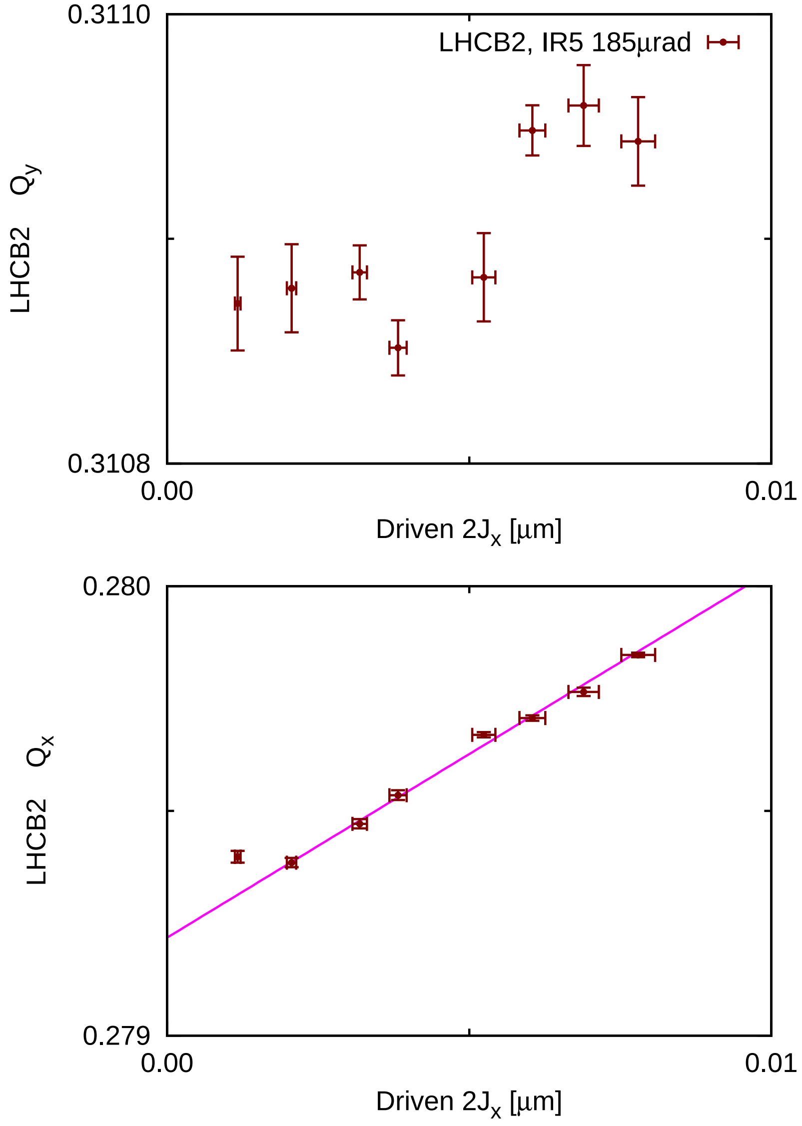

Figure 3: Measured detuning of LHC Beam 2 with horizontal amplitude with the IR5 crossing angle applied.

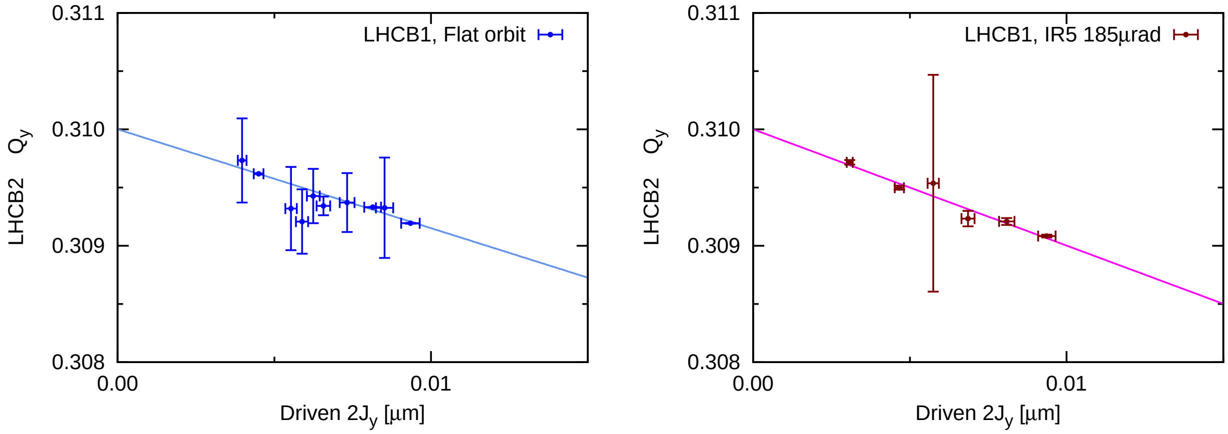

Figure 4: Measured direct amplitude detuning of LHC Beam 1 with and without the IR5 crossing angle applied.

reliable measurement.

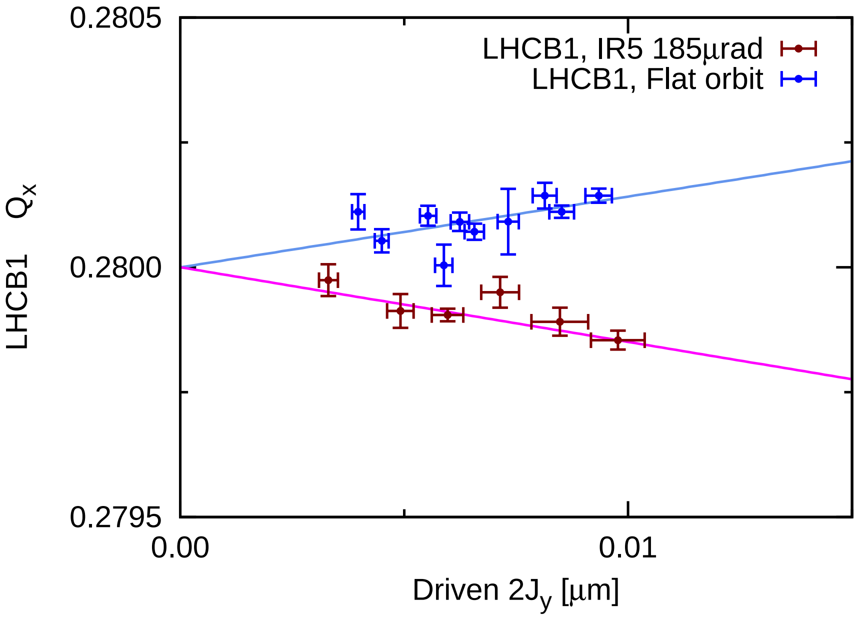

Figure 5: Measured cross-term amplitude detuning of LHC Beam 1 with and without the IR5 crossing angle applied.

Table 2 summarizes the results of the amplitude detuning measurements. The results of measurements performed with flat orbit during 2016 commissioning are also quoted. Figure 6 and 7 show histograms of the predicted change in first-order detuning coefficients upon application of a $185\,\mu\mathrm{rad}$ crossing angle in IR5 obtained via PTC simulation. The PTC model included magnetic errors in the experimental insertions of greater than octupole order, based upon sixty seeds generated by 2015 WISE tables.

Table 2: Measured first-order detuning coefficients obtained from linear fits to AC-dipole detuning data. Quoted coefficients have already been adjusted for the effect of the driven oscillations. Quoted uncertainties are the $1\,\sigma$ standard error on the fit parameters. The reduced χ^2 is given as a measure of goodness of fit.

	$\partial Q/\partial(2J)$ $[10^3\mathrm{m}^{-1}]$		
	2016 commissioning: Flat orbit	**MD: Flat orbit**	**MD: IR5@**$185\,\mu\mathrm{rad}$
$\frac{\partial Q_y}{\partial(2J_y)}_{\mathrm{LHCB1}}$	-50 ± 1 $(\chi^2_{red} = 0.2)$	-42 ± 2 $(\chi^2_{red} = 0.5)$	-50 ± 3 $(\chi^2_{red} = 1.4)$
$\frac{\partial Q_x}{\partial(2J_y)}_{\mathrm{LHCB1}}$	0.1 ± 1 $(\chi^2_{red} = 3.8)$	15 ± 5 $(\chi^2_{red} = 1.5)$	-15 ± 5 $(\chi^2_{red} = 1.1)$
$\frac{\partial Q_y}{\partial(2J_y)}_{\mathrm{LHCB2}}$	-44 ± 1 $(\chi^2_{red} = 0.4)$	-43 ± 1 $(\chi^2_{red} = 0.5)$	-44 ± 1 $(\chi^2_{red} = 0.2)$
$\frac{\partial Q_x}{\partial(2J_y)}_{\mathrm{LHCB2}}$	0.3 ± 1 $(\chi^2_{red} = 0.2)$	10 ± 1 $(\chi^2_{red} = 4.5)$	7 ± 1 $(\chi^2_{red} = 1.8)$
$\frac{\partial Q_x}{\partial(2J_x)}_{\mathrm{LHCB2}}$	38 ± 1 $(\chi^2_{red} = 0.6)$		41 ± 1 $(\chi^2_{red} = 0.6)$

In LHC Beam 2 measurements were consistent with no observation of feed-down from higher order errors in the insertion region. Comparing to simulation this is very much on the low end of the

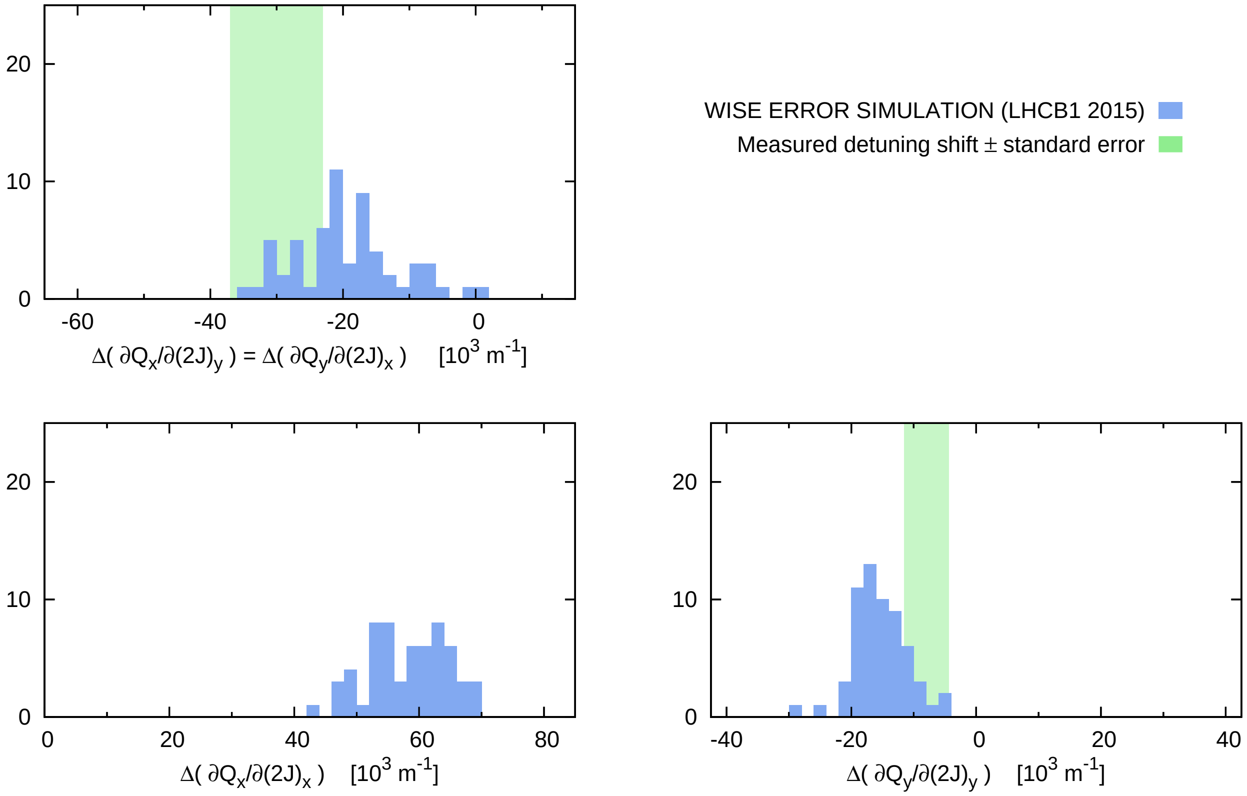

Figure 6: Predictions from PTC of detuning shifts in LHC Beam 1 upon application of the IR5 crossing angle. Predictions are based on either the new (blue) or old (red) WISE models for the LHC.

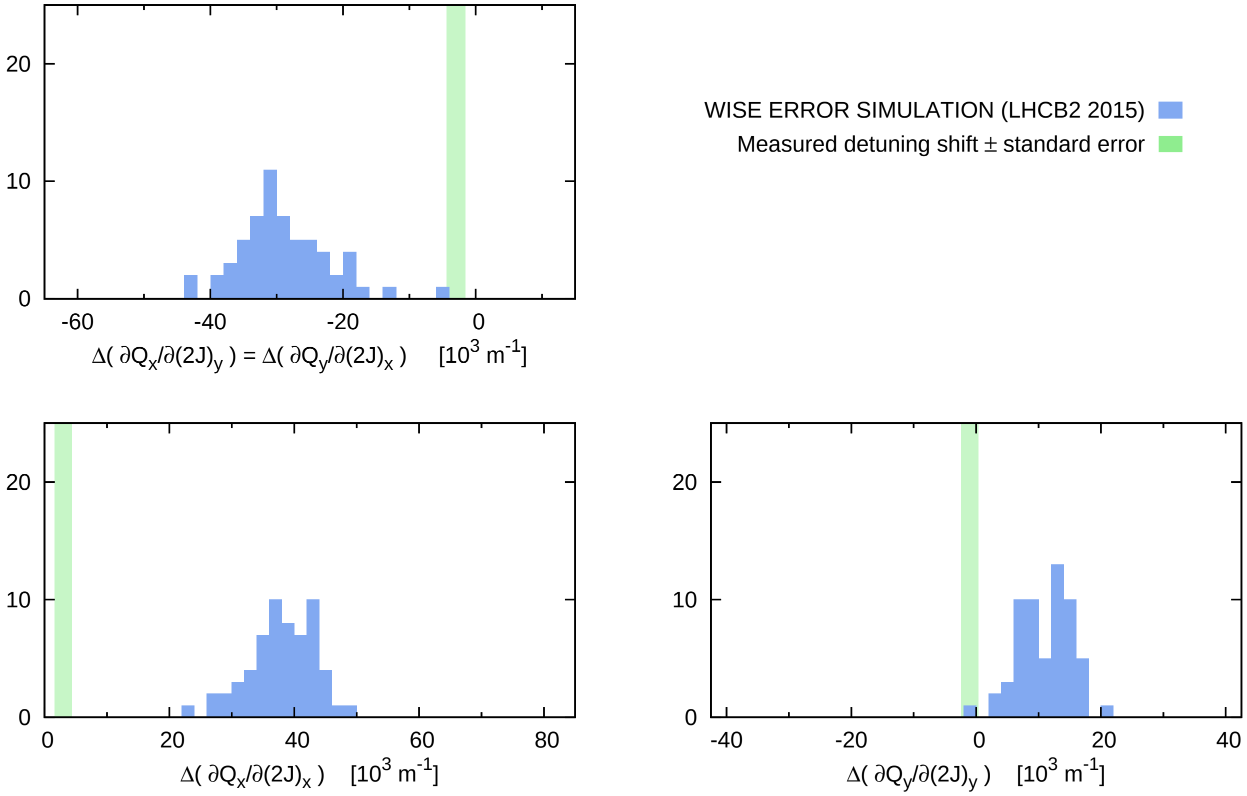

Figure 7: Predictions from PTC of detuning shifts in LHC Beam 2 upon application of the IR5 crossing angle. Predictions are based on either the new (blue) or old (red) WISE models for the LHC.

WISE predictions for the cross-term and direct vertical detuning. It is inconsistent with simulation for the horizontal direct term. Observations of LHC Beam 1 are less clear. Detuning coefficients with flat orbit appear to have changed slightly since 2016 commissioning. Unlike Beam 2 there were non-negligible shifts in the fitted detuning coefficients upon application of the crossing angle in IR5. Unfortunately measurement quality was quite poor due to earlier blow-up of the beams. It seems somewhat strange that the shift to detuning coefficients should be so inconsistent between the two LHC Beams, since main sources of feed-down are expected in the common regions. The observations of Beam 1 certainly motivate additional measurements in the future, with better beam quality allowing a larger range of actions to be probed. None-the-less, given the overall quality of the observations made during this MD it seems it should be possible to confidently measure detuning shifts at the level of $10^1 \times 10^3\,\mathrm{m}^{-1}$ due to high-order feed-down. Contrasting to the expected shifts in the HL-LHC shown in Fig. 1, which predicts detuning changes up to an order of magnitude greater than this level, the use of feed-down to amplitude detuning as an observable for compensation of high-order nonlinearities in the experimental insertions is a realistic proposal.

4 Conclusions

First measurements of amplitude detuning with IR-crossing schemes applied have been performed at top energy in the LHC. This has allowed a first beam-based examination of nonlinear errors in the experimental insertions of greater than octupole order, feed-down from which may become particularly significant in the HL-LHC. Measurements of the direct detuning terms in LHC Beam 2 were successful in-spite of reduction of the available physical aperture upon application of the crossing angle orbit bump. Measurement of the cross-term detuning was more difficult, however this was a feature of the small value in the machine. At operationally significant levels, it was possible to measure the ampliutde-detuning at top energy with crossing scheme applied.

In-spite of the aforementioned success, the measurement is challenging. Observations of Beam 1, which had been blown-up during an earlier MD study, demonstrate the importance of a beam quality to these studies. Bunches require sufficient intensity to give a good signal in turn-by-turn BPM data, and a small emittance to allow large-amplitude kicks to be applied. Comparing the measured detuning to predictions of simulation also raises some interesting questions. Beam 2 measurements showed no substantial changes to the tune footprint as a result of feed-down in IR5. While of lower quality, measurements of Beam 1 did appear to show non-negligible shifts to the detuning coefficients. Understanding these observations will require further study, and in particular improved quality measurements of Beam 1. On the longer term, understanding the role played by the high-order errors in affecting tune footprint will require the separation of decapole and dodecapole contributions, and hence detuning measurements at several crossing angles. The other experimental insertions also remain to be studied.

This MD represents a first step in validating a new method to study high-order nonlinear errors in experimental insertions. Given the measurement quality obtained, even under comparatively challenging conditions, feed-down to detuning appears to be a realistic proposal for study and compensation of decapole errors in the HL-LHC.

5 Acknowledgments

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