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Report from MD380: Nonlinear errors in experimental insertions and off-momentum dynamic aperture

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Summary

Nonlinear errors in low-β^* insertions can have a significant impact upon the beam-dynamics. In particular reductions in the LHC dynamic aperture of the order of $3\,\sigma_{\mathrm{nominal}}$ (10^5 turns) are expected due to the presence of such errors in IR1 and IR5 at $\beta^* = 0.4\,\mathrm{m}$. This represents a slight risk to $40\,\mathrm{cm}$ operation in 2016. More optimistically correction of nonlinear errors in experimental insertions has led to significant gains in luminosity production in other accelerators: a $\geq 4\,\%$ increase in integrated luminosity per fill was achieved in RHIC from the correction of such errors. The nonlinear errors of the ATLAS and CMS insertions were therefore studied at top energy during machine development time in 2015. During one of these studies it was also possible to perform AC-dipole kicks at injection, which have indicated a reduction in dynamic aperture off-momentum.

Contents

1 Introduction

Nonlinear errors in experimental insertions can have a significant impact on beam dynamics in the LHC. Correspondingly large rewards to accelerator performance and luminosity production can therefore be gained through their correction. As an example, correction of normal decapole and dodecapole errors in the RHIC experimental insertions generated a $4\,\%$ increase in the integrated luminosity per fill [1]. During LHC Run I the nonlinear errors in the ATLAS and CMS insertions were studied via their feed-down to tune and linear coupling under the influence of varying closed orbit bumps through the IRs [2]. These same techniques were applied during machine development in 2015, with the aim of further studying the errors and testing corrections prior to $40\,\mathrm{cm}$ operation in 2016.

2 MD description

MDs to study nonlinear errors in the IRs were allocated in MD blocks 2 and 3. The first MD took place between 31-08-2015 00:00 and 31-08-2015 06:00 (FILL:4302-4303). A single bunch ($10^{10}\,[\mathrm{p}]$) at $6.5\,\mathrm{TeV}$ was squeezed to $\beta^* = 0.4\,\mathrm{m}$. Upon arriving at $0.4\,\mathrm{m}$ an AC-dipole based coupling correction was applied. Due to a trip of $\mathrm{RQSX3.R1}$ the time available for measurements was extremely limited. Two closed orbit scans were performed in the crossing angle planes of IR1 and IR5. The crossing angle knobs were varied in $\sim 20\,\mu\mathrm{rad}$ increments, and feed-down from nonlinear errors was monitored using the BBQ system. Good quality data was obtained for the tunes, however linear coupling data was unusable due to substantial noise on the measurements.

The second MD took place between 06-11-2015 20:00 and 07-11-2015 04:00 (FILL:4593, BEAM-PROCESS: SQUEEZE-6.5TeV-80cm-40cm-v3-2015_V1@494_[END] and FILL:4594, BEAM-PROCESS: RAMP-6.5TeV-2015_MD1_40cm@0_[START]). The MD procedure for the second IR-nonlinear errors MD was intended to be similar to the first: utilizing a pilot bunch at $6.5\,\mathrm{TeV}$, $0.4\,\mathrm{m}$ to study the nonlinear errors via feed-down. In addition to the BBQ however, the feed-down was to be studied using the AC-dipole. Corrections for several nonlinear multipoles were also to be tested. Due to difficulties in correcting the closed orbit at Flattop arrival at $0.4\,\mathrm{m}$ was delayed. Upon reaching $0.4\,\mathrm{m}$ and initiating a closed orbit scan through IR1 the beams were dumped by a trip of $\mathrm{RSD1.A34B2}$, $\mathrm{RSF1.A34B2}$ and $\mathrm{RSF2.A34B2}$. Problems with the LHC Beam Dump System following the precycle then prevented injection until there was not enough time remaining in the MD to perform another ramp to top energy. No data regarding the nonlinear errors in the experimental insertions was therefore obtained from this MD. While not enough time remained to study the IR nonlinear errors, during the final hour of the allocated MD block it was possible to inject Beam 2 (but not Beam 1) and AC-dipole kicks were performed at injection, both on-momentum and at $\frac{\delta p}{p} = \pm 0.8 \times 10^{-3}$.

3 Nonlinear corrector circuits

Table 1 details the maximum powering of the nonlinear corrector circuits in the LHC experimental insertions. Note these are the limits for the 2015 nominal powering of the orbit correctors used for the crossing angles. It may be possible to have greater margins for the b_3 and b_6.

Table 1: Maximum possible currents in the nonlinear corrector circuits in the LHC experimental insertions, for nominal powering of the RCBXH3 and RCBV3.

Multipole	Circuit	Maximum powering $[\mathrm{A}]$
a_3	RCSSX3.L1	50
	RCSSX3.R1	100
b_3	RCSX3.L1	10
	RCSX3.R1	10
a_4	RCOSX3.L1	NOT AVAILABLE
	RCOSX3.R1	100
b_4	RCOX3.L1	100
	RCOX3.R1	100
b_6	RCTX3.L1	10
	RCTX3.R1	10
a_3	RCSSX3.L2	NOT AVAILABLE
	RCSSX3.R2	100
b_3	RCSX3.L2	10
	RCSX3.R2	10
a_4	RCOSX3.L2	NOT AVAILABLE
	RCOSX3.R2	100
b_4	RCOX3.L2	NOT AVAILABLE
	RCOX3.R2	100
b_6	RCTX3.L2	10
	RCTX3.R2	10
a_3	RCSSX3.L5	100
	RCSSX3.R5	100
b_3	RCSX3.L5	10
	RCSX3.R5	10
a_4	RCOSX3.L5	100
	RCOSX3.R5	100
b_4	RCOX3.L5	100
	RCOX3.R5	100
b_6	RCTX3.L5	10
	RCTX3.R5	10
a_3	RCSSX3.L8	100
	RCSSX3.R8	100
b_3	RCSX3.L8	10
	RCSX3.R8	10
a_4	RCOSX3.L8	100
	RCOSX3.R8	100
b_4	RCOX3.L8	100
	RCOX3.R8	100
b_6	RCTX3.L8	10
	RCTX3.R8	10

The restrictions imposed by these powering limits are not currently believed to limit the ability to correct the nonlinear errors in the experimental insertions. However, during the second IR-nonlinear errors MD attempts to trim the octupolar correctors in IR1 failed. In particular, when the magnetic strength of the circuits $\mathrm{RCOSX3.L1}$ and $\mathrm{RCOSX3.R1}$ were trimmed at K level, the correction was not propagated to the next parameters in the hierarchy ($\mathrm{K\_smooth}$, I and $\mathrm{I\_ref}$) and consequently never driven to the power converter. An offline analysis indicates that the problem was most likely due to zero settings contained in the knob $\mathrm{LHCBEAM/TRIPLET\_CORR\_IP1\_ON}$. This is a special knob directly connected to the $\mathrm{K\_smooth}$ level, which allowS it to work like a switch. When the knob contains 1 the corrections are active, but when the knob contains zero, the K level of the triplet correctors are not transmitted downstream the parameter chain. Special attention should be

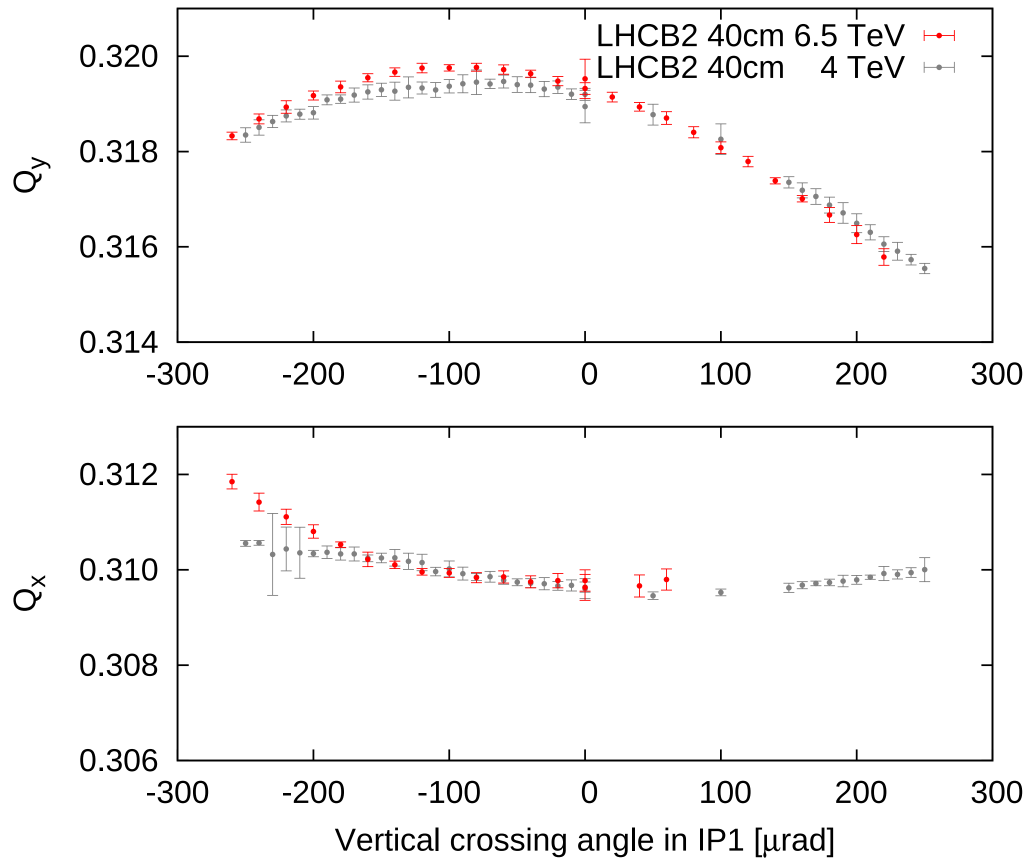

Figure 1: Comparison between feed-down to tune with changes of vertical crossing angle in IR1, measured in 2012 ($4\,\mathrm{TeV}$) and 2015 ($6.5\,\mathrm{TeV}$).

paid to these settings during future correction attempts, however the difficulties encountered during this particular MD did not influence its outcome, as the measurement was curtailed due to hardware issues before it would have been possible to measure any corrected configuration.

4 IR nonlinear error measurements

Scans of the vertical crossing angle in IR1 were performed at $0.4\,\mathrm{m}$ in 2012 and during 2015. Figure 1 shows a comparison of the feed-down measured in 2012 compared to that seed during the 2015 MD. The feed-down from the nonlinear errors in IR1 observed in 2015 is consistent with that seen in 2012. This suggests that corrections of the nonlinear errors calculated from 2012 MD data should still be valid for commissioning in 2016. As no measurements of IR5 were performed at $0.4\,\mathrm{m}$ during Run 1 no comparison is possible for this IR.

Measurements of the feed-down were compared to MAD-X simulations including nonlinear errors in the insertions determined from magnetic measurements. Figure 2 shows the comparison between modelled and measured feed-down with vertical crossing angle in IR1. As in 2012 a substantial discrepancy is observed between the predicted and observed linear tune variation, corresponding to feed-down from a_3. Octupolar feed-down to Q_y agrees very well between model and measurement, feed-down to Q_y from multipoles of higher-than-octupole order appears smaller in the measured data than predicted by the magnetic measurements. Feed-down to Q_x shows significant feed-down from multipoles higher than sextupole order. This is consistent with studies from Run 1 [2], but from the data collected so far it is not possible to determine from which multipole order the feed-down occurs. This will be further studied by combining the feed-down observations with measurements of the detuning with amplitude performed in a separate MD.

Figure 3 shows the comparison between modelled and measured feed-down with horizontal crossing angle in IR5. Substantial differences are seen between the measured feed-down and the predictions of the magnetic model which have yet to be understood. It is noted though that in general the feed-down from octupole observed in the machine appears to be significantly smaller than that predicted by the magnetic measurements. This situation is qualitatively similar to that observed in IP5 at $0.6\,\mathrm{m}$ in 2012.

5 Dynamic aperture at injection

AC-dipole kicks were performed in the horizontal plane on- and off- momentum ($\frac{\delta p}{p} = \pm 0.8 \times 10^{-3}$) at injection. Kicks were made with increasing amplitudes from $2\,\%$ to $18\,\%$ of the maximum AC-dipole excitation and driven tune offsets of ± 0.012 (corresponding to an amplitude range of approximately 0.4 - $2.5\,\sigma_{\mathrm{nominal}}$). Kicks on-momentum and at $\frac{\delta p}{p} = -0.8 \times 10^{-3}$ showed beam-losses typical to AC-dipole excitation, namely a step-like drop in intensity at the time of the kick followed by a return to the previous lifetime after driven oscillations end. Beam intensity data for these two configurations are shown in Figs. 4 and 5.

When identical kicks were performed at $\frac{\delta p}{p} = +0.8 \times 10^{-3}$ however, losses were observed to persist long after the AC-dipole excitation had ended. These slow losses, shown in Fig. 6, are characteristic of beam-loss from the dynamic aperture. Such slow losses are observed even for very small kicks ($0.4\,\sigma_{\mathrm{nominal}}$), indicating a sizable reduction in the DA for an off-momentum beam.

It should be noted that the beam-losses following the AC-dipole excitiations cannot be straightforwardly related to dynamic aperture as in the case of a single kick or losses from an unkicked beam. Dynamic aperture of a beam under the influence of driven oscillations differs from that of undriven motion, while blow-up during the AC-dipole excitation alters the beam-profile from which losses occur following the end of AC-dipole excitation.

6 Conclusions

Two crossing angle scans have been performed in 2015 to study feed-down from nonlinear errors in LHC experimental insertions IR1 and IR5 at $6.5\,\mathrm{TeV}$, $0.4\,\mathrm{m}$. The observed feed-down in IR1 is very similar to that observed for the same optics but lower energy in 2012. In IR5 the situation is qualitatively similar to that at $0.6\,\mathrm{m}$ in 2012, however no direct comparison is possible as no $0.4\,\mathrm{m}$ measurements were made during Run 1. Large discrepancies remain between predicted and observed feed-down from a_3 and b_3 in IR1 and IR5 respectively. b_4 errors in IR5 appears significantly smaller than expected. Octupolar feed-down to Q_y in IR1 is consistent with the predictions of the LHC magnetic model, while discrepancies of octupole or higher order appear in the feed-down to Q_x. These errors will continue to be studied with the aim of implementing corrections in 2016.

While it was not possible to perform any measurements of the nonlinear errors in the IRs during the second MD block allocated for these activities, AC-dipole kicks at injection did reveal a substantial reduction in the dynamic aperture when shifting the beam to positive $\frac{\delta p}{p}$. These observations remain to be analysed in more detail.

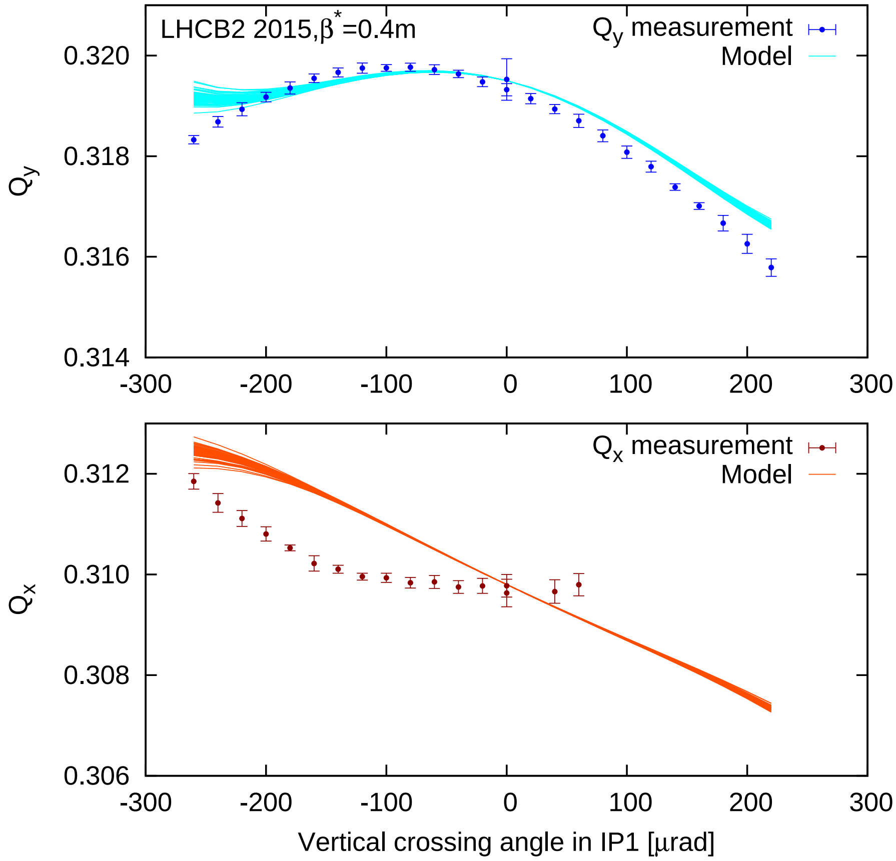

Figure 2: Comparison between measured and simulated feed-down to tune in IR1.

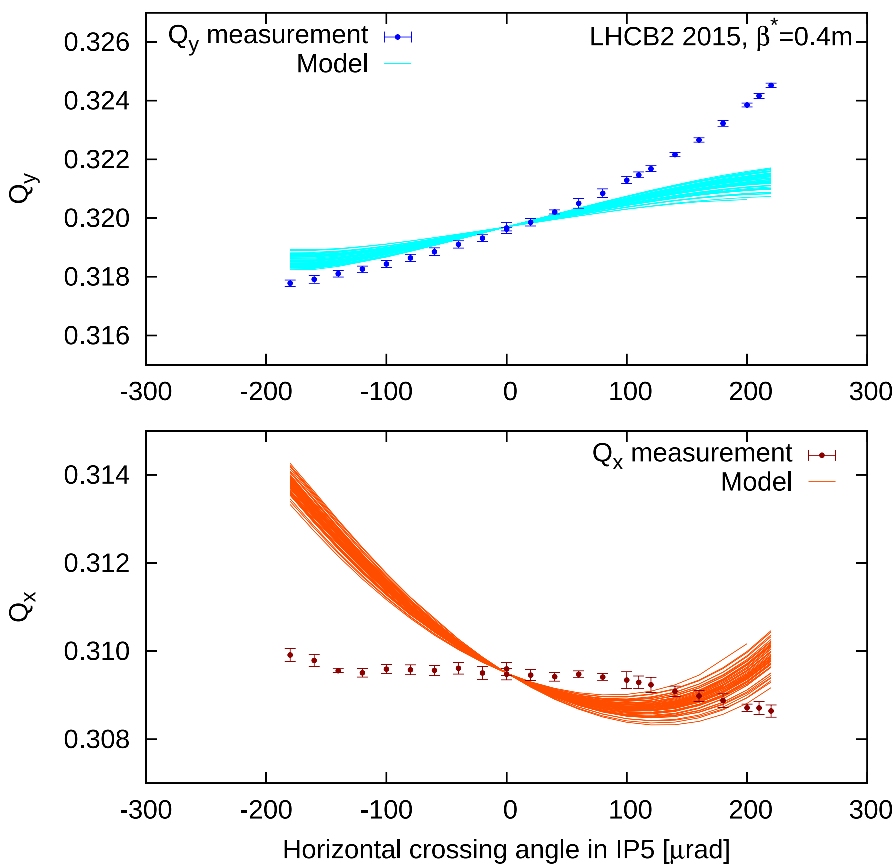

Figure 3: Comparison between measured and simulated feed-down to tune in IR5.

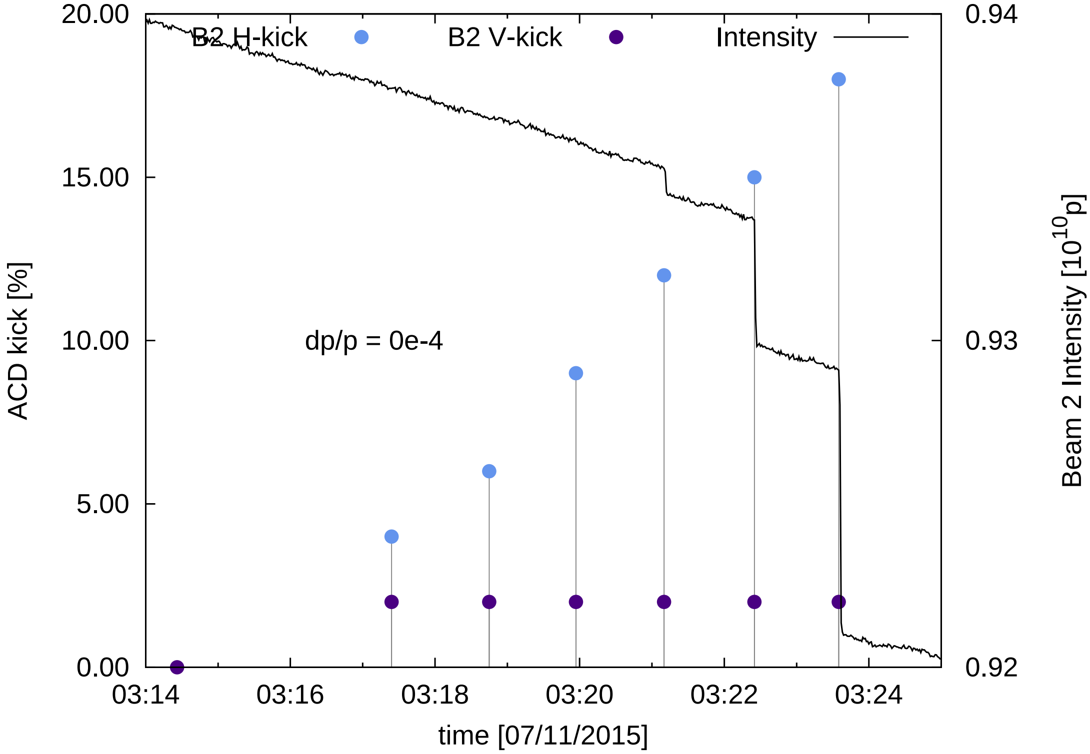

Figure 4: Measured beam intensity following horizontal AC-dipole kicks on-momentum at injection

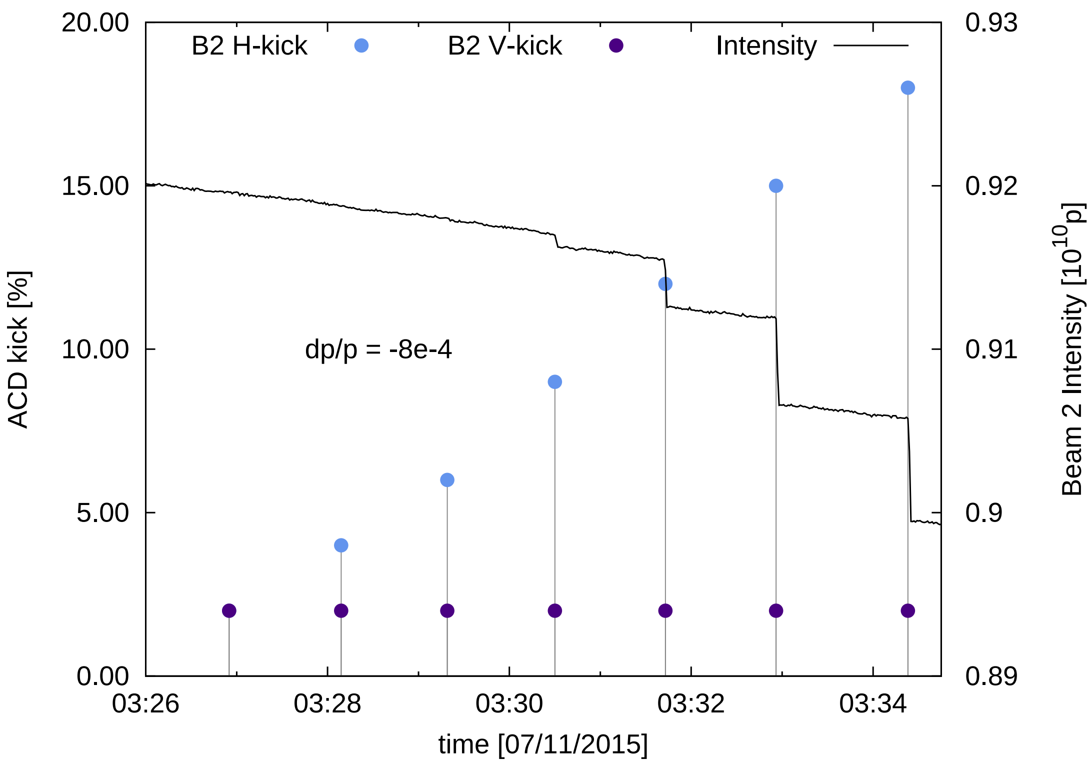

Figure 5: Measured beam intensity following horizontal AC-dipole kicks with $\frac{\delta p}{p} = -0.8 \times 10^{-3}$ at injection.

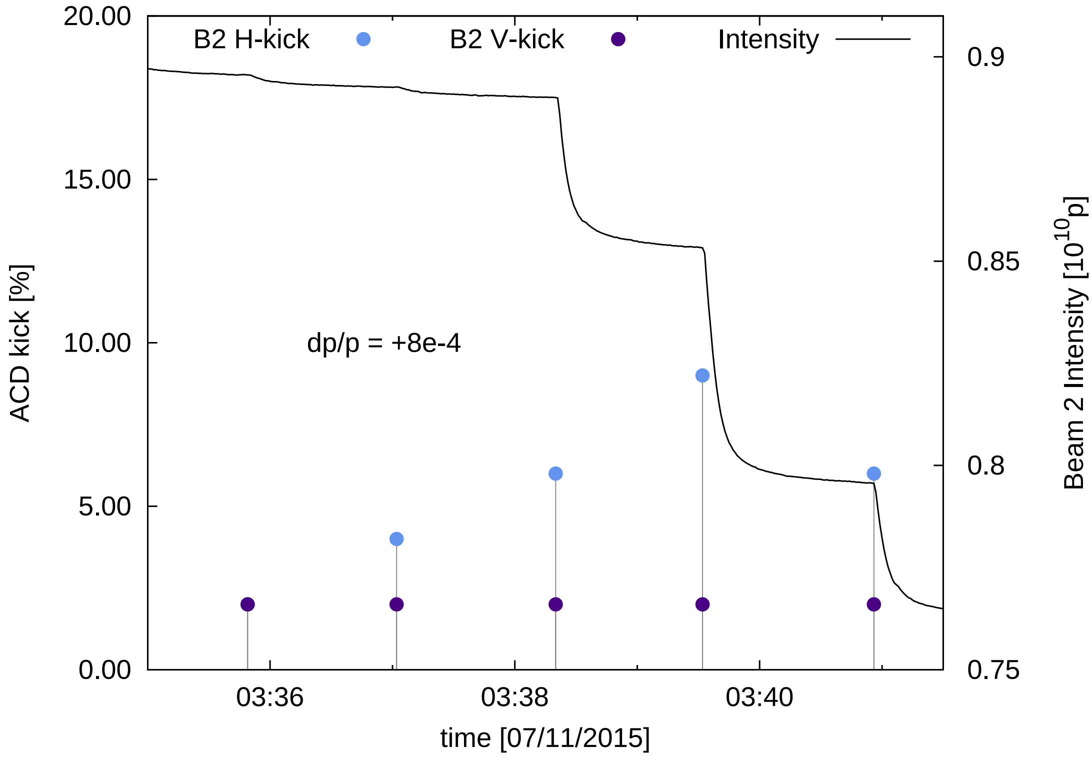

Figure 6: Measured beam intensity following horizontal AC-dipole kicks with $\frac{\delta p}{p} = +0.8 \times 10^{-3}$ at injection.

7 Acknowledgments

Many thanks go to the OP group for their support of these studies, and Kajetan Fuchsberger for providing support and advice in regard to both the nonlinear corrector circuits in the IRs and the limits on crossing schemes in IR1 and IR5. Thanks also go to Belen Maria Salvachua Ferrando who prepared a collimation sequence for the IR-nonlinear errors MD. Many thanks to Giulia Papotti who acted as LHC Engineer in Charge for the IR-nonlinear errors study.

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