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CONTROLLING LANDAU DAMPING VIA FEED-DOWN FROM HIGH-ORDER CORRECTORS IN THE LHC AND HL-LHC*

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Abstract

Amplitude detuning measurements in the LHC have shown that a significant amount of detuning is generated in Beam 1 via feed-down from decapole and dodecapole field errors in the triplets of the experiment insertion regions, while in Beam 2 this detuning is negligible. In this study, we investigate the cause of this behavior and we attempt to find corrections that use the feed-down from the nonlinear correctors in the insertion region for amplitude detuning.

INTRODUCTION

After correction of octupolar (b_4) errors, residual amplitude detuning in Beam 1 was measured during the LHC commissioning 2018, when the crossing orbit bumps were enabled [1, 2]. Further investigation [3] confirmed this finding and revealed the main contribution to be feed-down from high-order errors, i.e. decapole (b_5) and/or dodecapole (b_6) errors, to the octupole fields, due to the crossing schemes in the Interaction Point (IP) 5 and IP 1.

Throughout, b_n and a_n are used to name normal and skew relative field errors and K_n and J_n to indicate normal and skew field strengths. All field indices begin at $n = 1$ for dipole fields. The machine settings are given in Table 1, while the measurements are summarized in Table 2.

The magnitude of the amplitude detuning is comparable with the detuning which had been corrected with the octupole correctors. This amount of detuning is detrimental to the accuracy of the base-band tune (BBQ) measurement [4] and likely also to dynamic aperture and beam lifetime, which has only been tested and confirmed for lower β^* [4].

The harmful influence of b_5 and b_6 errors on dynamic aperture and beam lifetime in the upcoming High-Luminosity LHC (HL-LHC) has been shown in simulations and dedicated measurements, in which the b_6 errors were artificially increased to replicate the HL-LHC conditions [5–9].

In this paper, a correction option is explored to correct b_6 by targeting observed amplitude detuning from feed-down in the LHC by utilizing the feed-down to b_4 from the dodecapole correctors in the nonlinear corrector packages of the insertion regions (IRs).

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Table 1: Machine Settings used During Measurements

Tunes:		$Q_x = 0.31$, $Q_y = 0.32$
Optics:		$\beta^* = 30$ cm round optics
Comissioning		28 . 04 . 2018
Crossing:	IP-Plane	[IP1-V / IP2-V / IP5-H / IP8-H]
(half angles)	µrad	[160 / 200 / 160 / -250]
Separation:	IP-Plane	[IP1-H / IP2-H / IP5-V / IP8-V]
	mm	[-0.55 / 1.4 / 0.55 / 1.0]
MD3311		16 . 06 . 2018
Crossing:		IP5-H 160 µrad (half angle)
Separation:		IP5-V 0.55 mm
Offset:		IP5-V −1.8 mm

AMPLITUDE DETUNING FROM FEED-DOWN

In thin lens approximation, as used for corrections calculated from simulations, multipole elements are split into single kicks at s_w surrounded by drift spaces, the kick strength being $K_n L_w$ - the integrated strength over the length L of element w. The β-function and orbit are then also approximated using the value at s_w.

The contribution to first order amplitude detuning from octupole fields of elements with integrated strength $K_4 L_w$ can be calculated [10] from

$$\frac{\partial Q_x}{\partial(2J_x)} = \frac{K_4 L_w}{32\pi}\beta_x^2(s_w) \quad (1)$$

$$\frac{\partial Q_x}{\partial(2J_y)} = \frac{\partial Q_y}{\partial(2J_x)} = -\frac{K_4 L_w}{16\pi}\beta_x(s_w)\beta_y(s_w) \quad (2)$$

$$\frac{\partial Q_y}{\partial(2J_y)} = \frac{K_4 L_w}{32\pi}\beta_y^2(s_w) \quad (3)$$

with the actions $J_{x,y}$. Including feed-down [11] due to the orbit x, y from normal and skew decapoles (K_5, J_5) and normal and skew dodecapoles ($K_6 L$, $J_6 L$) we get

$$K_4 L \mapsto K_4 L + xK_5 L + yJ_5 L + \frac{1}{2}\left(x^2 - y^2\right)K_6 L + xyJ_6 L\,. \quad (4)$$

In the following chapters the symbols

$$Q_{a,b} = \frac{\partial Q_a}{\partial(2J_b)}, \quad \text{and} \quad \tilde\beta_{a,b} = \begin{cases} \tilde\beta_{x,x} = \frac{\beta_x^2}{32\pi} \\ \tilde\beta_{x,y} = -\frac{\beta_x\beta_y}{16\pi} \\ \tilde\beta_{y,y} = \frac{\beta_y^2}{32\pi} \end{cases} \quad (5)$$

will be used.

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Table 2: Summary of the relevant amplitude detuning measurements from 2018. Measurements for Beam 1 (top) and Beam 2 (bottom). Where AC-Dipole kicks were used, the results have been corrected for the effect of forced oscillations [12].

$[10^3\,\mathrm{m}^{-1}]$	Case	$\partial Q_x/\partial(2J_x)$	$\partial Q_y/\partial(2J_x)$	$\partial Q_x/\partial(2J_y)$	$\partial Q_y/\partial(2J_y)$	Ref.
2018 commissioning	6.5 TeV	34 ± 1	8 ± 2	18 ± 1	-38 ± 1	[1, 2]
full crossing @ +160 µrad	β^* = 0.3 m	-3 ± 1	-10 ± 3	-14 ± 2	13 ± 3	
2018 MD3311	6.5 TeV	0.8 ± 0.5	10 ± 1	8 ± 28	-3 ± 1	[3]
flat-orbit	β^* = 0.3 m	-7.5 ± 0.5	8 ± 2	-2 ± 1	6 ± 1	
2018 MD3311	6.5 TeV	56 ± 6	-9 ± 15	108 ± 24	3 ± 2	[3]
IP5 @ +160 µrad	β^* = 0.3 m	1.5 ± 0.5	4 ± 1	-4 ± 3	12 ± 1	

CORRECTION APPROACH

The dodecapole corrector elements MCTX left and right of either IP1 or IP5 can be used to compensate for the measured detuning. As the contributions to detuning add up linearly, an equation system can be built with these correctors as unkowns, targeting $-\Delta Q_{a,b}$, the change in detuning to correct between the measurements at flat-orbit and with crossing scheme applied:

$$\begin{pmatrix} B^{(B1)}_{a,b;L1} & B^{(B1)}_{a,b;R1} & B^{(B1)}_{a,b;L5} & B^{(B1)}_{a,b;R5} \\ B^{(B2)}_{a,b;L1} & B^{(B2)}_{a,b;R1} & B^{(B2)}_{a,b;L5} & B^{(B2)}_{a,b;R5} \\ & & \vdots & \end{pmatrix} \cdot \begin{pmatrix} K_6 L_{L1} \\ K_6 L_{R1} \\ K_6 L_{L5} \\ K_6 L_{R5} \end{pmatrix} = - \begin{pmatrix} \Delta Q^{(B1)}_{a,b} \\ \Delta Q^{(B2)}_{a,b} \\ \vdots \end{pmatrix}, \tag{6}$$

where the matrix elements are the detuning coefficients from Eq. (5) with feed-down from K_6 to K_4 (see Eq. (4))

$$B^{(B\#)}_{a,b;w} = \frac{1}{2}\left(x_w^{(B\#)^2} - y_w^{(B\#)^2}\right)\tilde{\beta}^{(B\#)}_{a,b;w}\,, \tag{7}$$

and using the subscript short-hands $L\#_{\mathrm{IP}}$, $R\#_{\mathrm{IP}}$ for the corrector elements left and right of the IP and $B\# \in \{B1, B2\}$ represents the beam. Equation (6) can be extended to include multiple targeted detuning terms $\Delta Q_{a,b}$. If local corrections - per IR - are required, Eq. (6) can be split into two equations' systems containing only the correctors of a single IR.

The measurement of the detuning cross-terms has proven to be very challenging in the past, and the cross-term values in Table 2 have been ignored for correction. Instead, they are either set to zero, or are transformed into inequalities, demanding $\Delta Q_{x,y}$ and $\Delta Q_{y,x}$ to be of negative value after correction, which, with the positive polarity of the Landau octupole currents in Run 3, assures beam stability [13]. The inequalities are used as boundary conditions while optimizing the convex problem of Eq. (6), for which the python package CVXPY [14, 15] has been utilized.

SIMULATION SETUP

In simulations, the nominal LHC is recreated in cpymad [16], a python wrapper for MAD-X [17], using the Run 2 sequence and 30 cm round optics. There are no errors applied. The orbit is then set up according to the desired realization, either full-crossing or crossing only in IP5, as described in Table 1.

From the optics functions, obtained from TWISS in MAD-X, the desired equation systems (Eq. (6)) are built and solved or optimized. To check the validity of the calculations, the resulting corrector strengths are applied and the actual detuning change determined from the PTC module [18, 19] as well as Eqs. (1) to (4).

The different scenarios are discussed in the next chapter.

SIMULATION RESULTS

A collection of the most meaningful simulated correction attempts can be found in Fig. 1. Shown are detuning values for correction, that is the opposite of the measured change in detuning between flat-optics and crossing scheme scenarios in Table 2.

Correcting IP5

In a first attempt only the dodecapole correctors of IP5 were utilized, as the biggest contribution to detuning stems from this IP. The results are shown in scenarios A–C in Fig. 1: When targeting a single term, e.g. the horizontal direct term (A), this specific term can be corrected very well, yet at the cost of the other terms. Especially, the large positive cross term in Beam 1, which is almost equal in magnitude to the corrected direct term, is of major concern for beam stability as mentioned above. Trying to match for the other terms, and in particular forcing the cross term to lower values (B: $0\,\mathrm{m}^{-1}$, C: $-50 \cdot 10^3\,\mathrm{m}^{-1}$), spoils the correction of the horizontal term drastically.

Global Corrections of IP1 and IP5

The option to correct the detuning "globally" using all four correctors in IP1 and IP5 has been explored in the scenarios D–F in Fig. 1: The measured global detuning can be well corrected, with very little residual detuning (D), even in the (untargeted) cross-terms, which is still positive at a few $10^3\,\mathrm{m}^{-1}$. Trying to reduce the cross-term residual by matching them to zero (E) or forcing them to be negative (F), spoils in turn the direct terms by a few $10^3\,\mathrm{m}^{-1}$. The contribution of the Beam 1 horizontal direct term from IP5 also matches very well the measured value of around $-52 \cdot 10^3\,\mathrm{m}^{-1}$, yet the other terms do not fit with the measured values in IP5.

Despite the good global agreement, we are hesitant to use them in the real machine, as they rely very heavily on the compensation between the two IPs. Other factors, such as dynamic aperture, might be spoiled upon introducing large, locally uncorrected changes to the optics. It would

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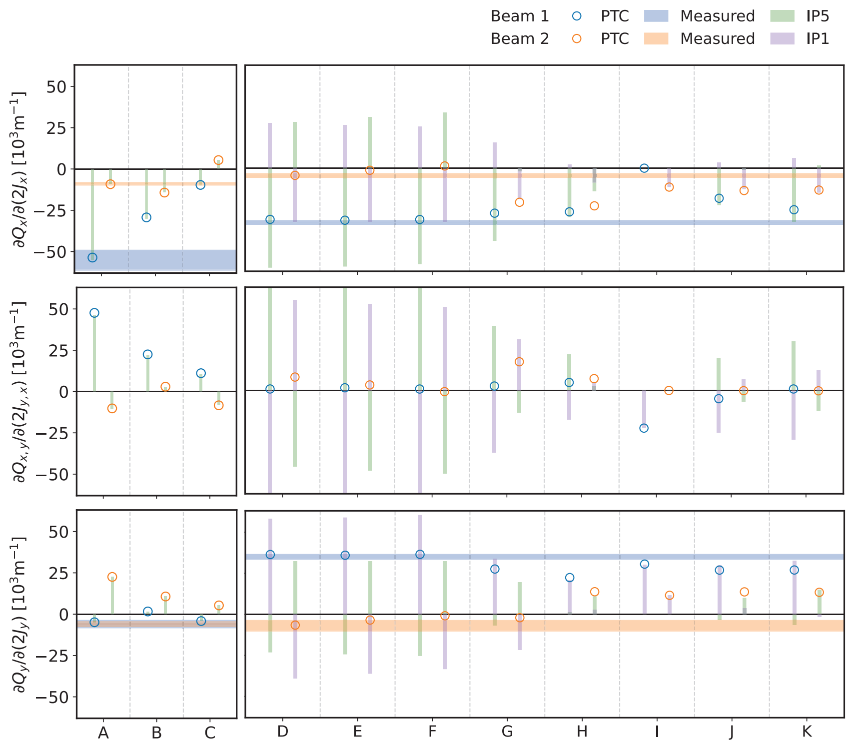

Target Scenarios [10^3 m^{-1}]

	$\Delta Q_{x,x}$ IP5	$\Delta Q_{x,x}$ IP1	$\Delta Q_{x,y}$ IP5	$\Delta Q_{x,y}$ IP1	$\Delta Q_{y,y}$ IP5	$\Delta Q_{y,y}$ IP1
A	-55.2	–	–	–	–	–
	-9	–	–	–	–	–
B	-55.2	–	0	–	-6	–
	-9	–	0	–	-6	–
C	-55.2	–	-50	–	-6	–
	-9	–	-50	–	-6	–
D	-33.2		–		35	
	-4.5		–		-7	
E	-33.2		0		35	
	-4.5		0		-7	
F	-33.2		≤0		35	
	-4.5		≤0		-7	
G	-55.2	22	–	–	-6	41
	-9	4.5	–	–	-6	-1
	+ global as in D					
H	-55.2	22	0	0	-6	41
	-9	4.5	0	0	-6	-1
I	-55.2	22	≤0	≤0	-6	41
	-9	4.5	≤0	≤0	-6	-1
J	-55.2	22	≤20	≤20	-6	41
	-9	4.5	≤20	≤20	-6	-1
	+ global as in F					
K	-55.2	22	≤30	≤30	-6	41
	-9	4.5	≤30	≤30	-6	-1
	+ global as in F					

Figure 1: Change in amplitude detuning for the direct terms in the X- (top) and Y- (bottom) plane and for the cross term (middle) after applying the calculated corrections determined by the scenarios as given in the table. For A–C only the IP5 crossing scheme is applied, for D–K the full crossing scheme is enabled (see Table 1). Circles show the results from PTC for Beam 1 (blue) and Beam 2 (orange), while vertical bars show the expected values as calculated by Eqs. (1) to (3), divided into contributions from IP5 (green) and IP1 (purple) and total. Where these bars overlap, they appear grey. The correction targets as measured are shown by the horizontal bands in the respective beam color.

therefore be favourable to control the local detuning using low corrector powering.

Localized Corrections of IP1 and IP5

Trying a local correction has proven to be very challenging, despite having 4 correctors available for matching, as seen in the attempts G–K in Fig. 1: Using all measured local and global values (G) gives large positive cross terms. Correcting for only the local terms while trying to keep the cross-terms low (H) does not match any of the terms very well, while forcing them to be negative (I) does not allow for a horizontal correction. Relaxing the cross term restriction locally but enforcing it globally (J and K) yields good compromises between all terms in the end, but spoils the cross term of Beam 1 in IP5.

The corrections from the scenario K look the most promising, as they replicate the measured local values best and allow for a compromise of the global correction of all measured terms, while keeping the cross terms locally limited. This correction uses 11% of the maximum corrector strength in the correctors L1 and R5 and only 1% in R1 and L5.

CONCLUSION AND OUTLOOK

In an attempt to correct decapole and dodecapole errors in the (HL-)LHC without decreasing Landau damping, a correction approach has been presented, directed at the feed-down to amplitude detuning. Several correction targets using the feed-down from the so far unpowered dodecapole correctors have been explored. While a perfect local correction of all three detuning terms is not feasible, controlling the detuning globally is possible and compromise solutions have been suggested, showing very promising results.

Better assessment of the cross term can help to improve upon the found corrections, but measuring these terms is very challenging.

Dodecapole corrections calculated by the presented method will be tested in the actual machine and with the hope to improve beam lifetime and dynamic aperture during the next (HL-)LHC runs.

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REFERENCES

[1] E. H. Maclean, "LHC optics commissioning in 2018," LMC Meeting, 2018, https://indico.cern.ch/event/733065/contributions/3023327/attachments/1658707/2656509/2018-05-30_LMC_2018commissioning.pdf/.

[2] E. H. Maclean, "Nonlinear optics MDs in 2018," HSS Meeting, 2018, https://indico.cern.ch/event/779845/contributions/3275039/attachments/1779557/2894503/2019_nonlinearMDs.pdf/.

[3] J. Dilly *et al.*, "Report and Analysis from LHC MD 3311: Amplitude detuning at end-of-squeeze," CERN, Accelerators & Technology Sector Note CERN-ACC-NOTE-2019-0042, 2019, p. 39. http://cds.cern.ch/record/2692810/.

[4] E. H. Maclean *et al.*, "New approach to LHC optics commissioning for the nonlinear era," *Phys. Rev. Accel. Beams*, vol. 22, no. 6, p. 061004, 2019. doi:10.1103/PhysRevAccelBeams.22.061004

[5] J. Dilly, M. Giovannozzi, R. Tomas, and F. F. Van der Veken, "Corrections of Systematic Normal Decapole Field Errors in the HL-LHC Separation/Recombination Dipoles", presented at the IPAC'22, Bangkok, Thailand, Jun. 2022, paper WEPOPT059, this conference.

[6] E. H. Maclean *et al.*, "Report from LHC MD 2158: IRnonlinear studies," Accelerators & Technology Sector Note CERN-ACC-2018-0021, 2018, p. 22. https://cds.cern.ch/record/2306295/.

[7] E. H. Maclean, "Prospect for high-order optics measurement in the High-Luminosity LHC," ABP Information Meeting, 2020, https://indico.cern.ch/event/960366/contributions/4039616/attachments/2113608/3555601/ABPinfo_v2.pdf/.

[8] E. H. Maclean, F. Carlier, J. Dilly, R. Tomás, and M. Giovannozzi, "Prospects for beam-based study of dodecapole nonlinearities in the CERN High-Luminosity Large Hadron Collider," submitted, 2022.

[9] J. Dilly *et al.*, "Report from LHC MD 3312: Replicating HL-LHC DA," CERN, Accelerators & Technology Sector Note to be published, 2022.

[10] J. Bengtsson and J. Irwin, "Analytical calculations of smear and tune shift," SSC Laboratory, Tech. Rep., 1990. https://inspirehep.net/literature/295132/.

[11] J. Dilly and R. Tomas, "A Flexible Nonlinear Resonance Driving Term Based Correction Algorithm With Feed-Down", presented at the IPAC'22, Bangkok, Thailand, Jun. 2022, paper WEPOPT061, this conference.

[12] S. White, E. H. Maclean, and R. Tomás, "Direct amplitude detuning measurement with ac dipole," *Phys. Rev. ST Accel. Beams*, vol. 16, no. 7, p. 071 002, 2013. doi:10.1103/PhysRevSTAB.16.071002

[13] N. Karastathis *et al.*, "LHC Run 3 Configuration Working Group Report," CERN, Tech. Rep., 2019, p. 12, https://cds.cern.ch/record/2750302/.

[14] S. Diamond and S. Boyd, "CVXPY: A Python-embedded modeling language for convex optimization," *J. Mach. Learn. Res.*, vol. 17, no. 83, pp. 1–5, 2016.

[15] A. Agrawal, R. Verschueren, S. Diamond, and S. Boyd, "A rewriting system for convex optimization problems," *J. Control Decis.*, vol. 5, no. 1, pp. 42–60, 2018. doi:10.1080/23307706.2017.1397554

[16] T. Gläßle, Y. I. Levinsen, and K. Fuchsberger, Cpymad: Cython binding to MAD-X, https://github.com/hibtc/cpymad/.

[17] CERN-Accelerator Beam Physics Group, Methodical Accelerator Design-MAD, http://madx.web.cern.ch/madx/.

[18] E. Forest, F. Schmidt, and E. McIntosh, "Introduction to the Polymorphic Tracking Code," SPS and LHC Division Note CERN–SL–2002–044 (AP), 2002, p. 149, http://cds.cern.ch/record/573082/.

[19] E. Forest, From Tracking Code to Analysis. Springer Japan, 2016. doi:10.1007/978-4-431-55803-3