CORRECTIONS OF SYSTEMATIC NORMAL DECAPOLE FIELD ERRORS IN THE HL-LHC SEPARATION/RECOMBINATION DIPOLES*

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Abstract

Magnetic measurements revealed that the new normal decapole (b_5) errors of the recombination dipoles (D2) for the HL-LHC could have a systematic component of up to 11 units. Based on previous studies, it was predicted that the current corrections would not be able to compensate this, thereby leading to a degradation of the dynamic aperture. On the other hand, the separation dipole D1 is expected to have a systematic b_5 component of 6 units to 7 units and its contribution to the resonance driving terms will partly compensate the effect of D2, due to the opposite field strength of the main component. Simulations were performed to address these concerns and to verify the compensation assumption, yet confirmed that the errors could only be partly compensated. In addition, various normal decapole resonance driving terms were examined as correction targets and the dependence of feed-down to amplitude detuning on this choice was discovered.

INTRODUCTION

During magnetic measurements it was found out that the b_5 values of the new D2 recombination dipoles (aka MBRD) in the High-Luminosity LHC (HL-LHC [1, 2]) might have a systematic b_5 component of up to 11 units [3]. Based on earlier studies, it was projected that the current correction scheme [4] will not be able to compensate these and that this will lead to a degradation of 0.5 σ to 1 σ in the Dynamic Aperture (DA) [1, 5]. In fact, contributions from D2 have not been incorporated into the correction scheme, as D2 is a dual aperture magnet, while the b_5 corrector is single aperture. Additionally, it is placed far away from the corrector package (CP, see Fig. 2 and [1]), leading to a large phase advance, lower β-function and different orbit. Hence it was uncertain, if the D2 inclusion would be beneficial to DA (see [5]). It was also investigated, whether the hitherto used Resonance Driving Term (RDT) f_{5000} was the optimal choice (see section “Closest Resonances”). Of further concern was the interplay between D2 and the other separation dipole, D1 (aka MBX). The new D1 is expected to have a systematic b_5 component of 6 units to 7 units [3]. Due to the opposite beam bending directions (see Fig. 2) in the two magnets, their contribution to the resonance driving terms will partly compensate. This is explored in section “Compensation”. Tracking simulations have been run to estimate the influence of the measured errors and to explore for their correction. The setup is described in section “Simulation Setup” and their findings are presented in section “Results”.

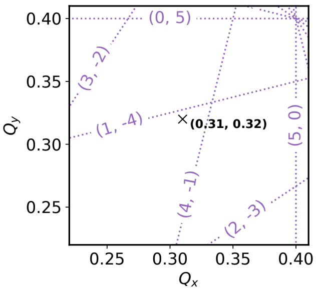

Figure 1: Tune diagram with HL-LHC collision working point and 5th order resonances.

CLOSEST RESONANCES

At collision energy, the HL-LHC has a design working point with fractional tunes of $Q_x = 0.31, Q_y = 0.32$. As seen in the tune diagram of Fig. 1, the closest normal decapole resonances are (1, -4), and (5, 0), which correspond to the RDTs f_{1004} and f_{5000}, respectively. With (1, -4) being the closest to the working point, one might assume that its influence might be the strongest and its correction the most beneficial. As the current implementation [6] on the other hand, chooses f_{5000} as correction target, its suitability was confirmed and the correction compared to targeting f_{1004}. The details are presented in the section “Results”.

COMPENSATION

One part of the investigation was to check whether the D1 and D2 b_5 errors might compensate each other. The reasoning behind this is that D1 and D2 have opposite bending angles (see Fig. 2). In fact, they have an integrated dipole strength value K_1L of equal magnitude, but of opposite signs. For the used optics (see section “Simulation Setup”) the b_5 of D2 needs to be about 3.1 times larger than the b_5 of D1 to cancel f_{5000} and 2.4 times larger to cancel f_{1004} in the RDT approximation used [4, 7]. The ratio of the estimated values of 6 units to 7 units for D1 and 11 units for D2, is about a factor 1.6 – 1.8 too low for total compensation, yet partial compensation has been observed and is described in section “Results”.

SIMULATION SETUP

The DA studies were performed with AutoSix [8], a SixDesk [9] wrapper, on top of a HL-LHC V1.4 MAD-X [10] setup: The HL-LHC lattice was created from the de-

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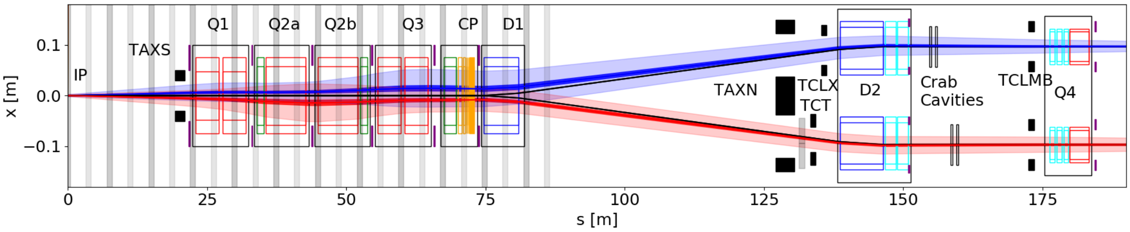


Figure 2: HL-LHC insertion region layout between the interaction point (IP) and Q4 [1].

fault sequence and magnetic field errors with crossing angles enabled at their nominal values, and at 7 TeV squeezed to $\beta^* = 15$ cm. The systematic b_5 values of the D1 ($b_{5,sys}^{D1}$) and D2 ($b_{5,sys}^{D2}$) were set to 0 units, 5 units, 10 units or 15 units to cover the estimated values as given in [3] with some additional margin. Other magnetic errors were realized from 60 different seeds, corresponding to either measurement errors from the WISE-tables [11] or random Gaussian distributed errors, leading to 60 different instances of the ring lattice for each scan point.

The magnetic errors of the main dipoles were corrected with the standard correction tools [12], while the magnetic errors of the insertion region were corrected by a python correction script [13], which allows for the flexibility of targeting different RDTs as needed in this study. As D1 is already integrated into the standard corrections, only the change of its systematic b_5 field component is considered. D2 has not been integrated into the nonlinear correction and it is either included "as a whole" in the corrections or omitted. Apart from the systematic b_5 error of the scan, the modelled D2 contains only random errors distributed over ±4 units so that any internal compensation would be visible in the seeds, as discussed in [14]. The correction is based on the approximate RDT calculation described in [4, 7]. Three different correction scenarios are investigated to distinguish between the origin and effects of the different error sources:

- **D1 b_5 & D2 uncorrected**: The standard corrections of the machine are performed, without the errors under test as described in the next two points.
- **correct D1 b_5**: As above, the standard corrections are performed, now including the systematic b_5 of D1. D2 is still not corrected.
- **correct D1 b_5 & D2**: D2 is here also fully included into the correction scheme. To calculate the correction the average error between the two apertures is considered.

Particles are initialized over 11 angles in the transverse plane for amplitudes between 2 σ and 20 σ (30 σ for flat orbit) in intervals of 2 σ containing 30 particle-pairs each. These are tracked for 100'000 turns with SixTrack [9], after which the surviving particles are registered and their amplitude calculated. The DA per angle can then be found by the largest amplitude of the surviving particles.

Statistics parameters, such as extrema, mean and standard deviation of the DA are gathered over the resulting 60 error instances and angles per scan point and correction scenario.

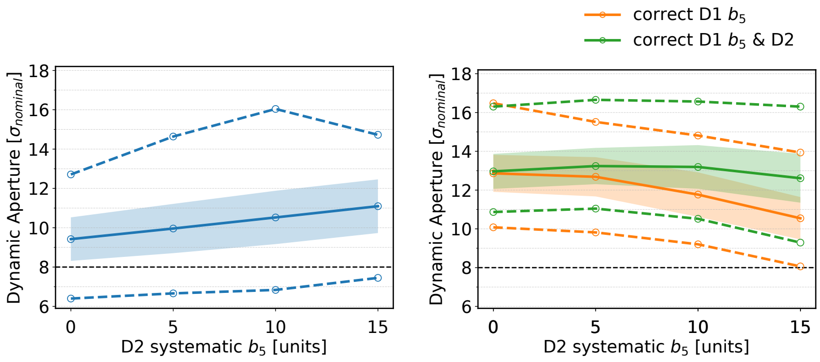
RESULTS

Figure 3a shows the expected compensation between $b_{5,sys}^{D1}$ and $b_{5,sys}^{D2}$ when sweeping over the systematic b_5 values of D2 without correction: As $b_{5,sys}^{D1} = 7$ units, the DA is worse at $b_{5,sys}^{D2} = 0$ units and gets larger with increasing $b_{5,sys}^{D2}$. Yet, the minimum DA (dashed blue line at the bottom) is always below the 8 σ needed to avoid degradation of beam intensity [1]. Correcting for D1 b_5 (orange data in Fig. 3b) increases the DA by up to 4 σ without $b_{5,sys}^{D2}$, but we see a steep decrease in DA, losing 1 σ (1.5 σ) in minimum (mean) DA at the expected error value of $b_{5,sys}^{D2} = 11$ units. Including D2 into the correction (green data), we can recover about 1 σ in minimum DA. This stems mostly from the random errors in D2 and the DA loss over $b_{5,sys}^{D2}$ is still present in the minimum DA, as visible at $b_{5,sys}^{D2} = 0$ units. The curve of the mean DA is flatter than that of the minimum DA in the investigated range, yet also shows DA loss from 10 units to 15 units. In conclusion, only a partial correction of the b_5 in D2 is possible.

The DA results in Fig. 4 and the corresponding amplitude detuning in Fig. 5 show that there is only little difference between targeting different RDTs when only D1 is corrected (Fig. 4a), yet f_{5000} performs better than f_{1004} when including D2 (Fig. 4b), in contrast to the expectation from section "Closest Resonances". Investigation of the residual amplitude detuning after correction, which is often an important factor for DA in the LHC [15, 16], in Fig. 5b indicates that it is the feed-down to b_4 (the field component driving amplitude detuning) from the b_5 in D2 due to the crossing orbit, which is better corrected targeting f_{5000}. This hints at b_5 feed-down still being present after correction, due to the orbit difference between the source (D2) and the corrector. D1, on the other hand, is very close to the corrector with negligible orbit difference. Turning the crossing angles off, as done in Figs. 4c and 5c, shows the expected behaviour of targeting f_{1004} resulting in larger mean DA and equal residual amplitude detuning.

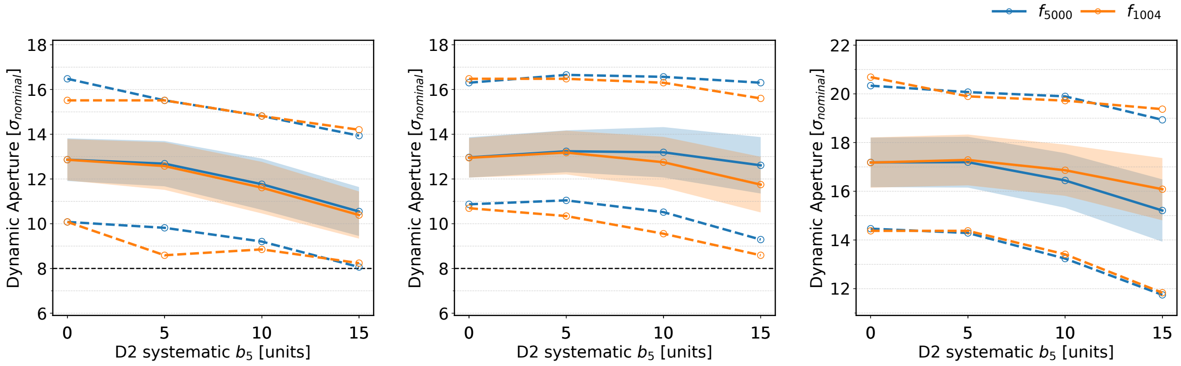
CONCLUSION AND OUTLOOK

It has been shown that inclusion of D2 into the nonlinear correction scheme for the high-luminosity insertion region of the HL-LHC is beneficial as its magnetic errors are partly corrected by the nonlinear corrector package. Full correction of D2 b_5 errors cannot be achieved due to its dual-aperture



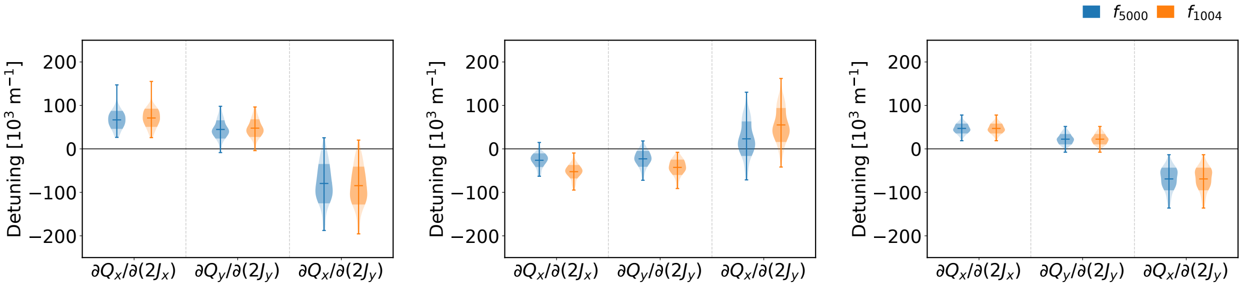
(a) D2 sweep at $b_{5,sys}^{D1} = 7$ units (b) D2 sweep at $b_{5,sys}^{D1} = 7$ units

Figure 3: DA simulation results for D2 sweeps targeting f_{5000}. Thick lines show the mean over all seeds and angles, dashed lines the respective minimum and maximum in the same set and the colored area one standard deviation.



(a) correct D1 b_5, w/ xing (b) correct D1 b_5 & D2, w/ xing (c) correct D1 b_5 & D2, flat orbit *note the y-range change!*

Figure 4: DA simulation results for D2 sweeps, targeting different RDTs at $b_{5,sys}^{D1} = 7$ units. Data representation as in Fig. 3.



(a) correct D1 b_5, w/ xing (b) correct D1 b_5 & D2, w/ xing (c) correct D1 b_5 & D2, flat orbit

Figure 5: Amplitude detuning simulation results, targeting different RDTs at $b_{5,sys}^{D1} = 7$ units, $b_{5,sys}^{D2} = 10$ units. The violins show a gaussian kernel density estimation of the realizations. Mean and extrema are indicated and one standard deviation emphasised.

nature, its phase advance and orbit difference to the corrector package. Compensation between the b_5 components of D1 and D2 is present, but alone is insufficient to achieve the required DA. With crossing orbit bumps in the IRs, the current RDT target f_{5000} is superior to f_{1004}, as feed-down to amplitude detuning is better corrected. For flat-orbit, f_{1004} is superior as expected from proximity of tunes to the resonance.

While this study was conducted, improvements to the magnet design were proposed, reducing the expected b_5 errors in D1 and D2 to 1 unit and 2 units respectively [17]. This aligns well with the results presented, indicating the errors should be kept below 5 units to allow correction and not spoil DA.

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