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CORRECTIONS OF NON-LINEAR FIELD ERRORS WITH ASYMMETRIC OPTICS IN LHC AND HL-LHC INSERTION REGIONS*†

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Abstract

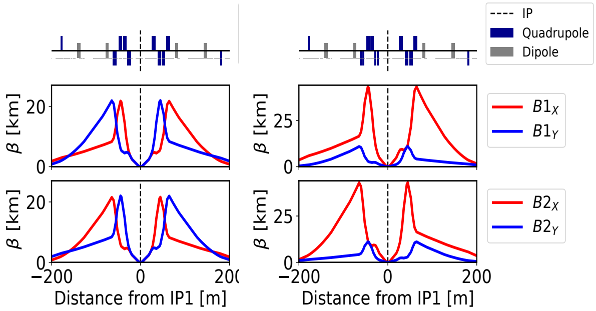
Existing correction schemes to locally suppress resonance driving terms in the error-sensitive high-beta regions of the LHC and HL-LHC have operated on the assumption of symmetric beta-functions of the optics in the two rings. As this assumption can fail for a multitude of reasons, such as inherently asymmetric optics and unevenly distributed errors, an extension of this correction scheme has been developed removing the need for symmetry by operating on the two separate optics of the beams at the same time. Presented here is the impact of this novel approach on dynamic aperture as an important measure of particle stability.

INTRODUCTION

The sensitivity of accelerator beam optics to magnetic errors depends directly on the β-function, which is highest in the surrounding insertion regions (IR) around the interaction points (IP) with the lowest β^* (the value of the β-function at the location of the IP). Hence, correcting the non-linear magnetic errors in these regions has been of significant importance in optimizing the LHC machine performance [1–5]. During the design phase of the LHC, it was envisaged to make use of the magnetic measurement data of the LHC magnets [6–8] to simulate the machine in MAD-X [9] and calculate the errors [10]. While it became clear that the accuracy of the magnetic model was not sufficient to calculate corrections to be implemented in the LHC [11], it has nevertheless been a useful tool for the estimation of linear and non-linear effects [5, 11–14].

With the installation of stronger magnets in the IR and the decrease of β^* in operation in the High Luminosity upgrade of the LHC (HL-LHC) [15, 16], the necessity for improved error and correction prediction is even greater in this high-performance machine.

To estimate the powering of the corrector magnets, a local correction scheme based on the Resonance Driving Terms (RDTs) in the IRs has been utilized [10]. Up to now, the implementation of this scheme calculated the correction based on a single input optics, for either Beam 1 or Beam 2, and made use of symmetries between the beams, to optimize the correction for both. Cases will occur in which this symmetry does not hold, e.g. through the introduction of feed-down [17], or the use of inherently asymmetric optics. An example for the latter are flat optics [18, 19], in which β^* in the two transversal planes no longer has identical values (see Fig. 1). These optics allow for a more distributed radiation deposition in the LHC magnets as well as an increase in luminosity [19]. Their feasibility has been studied during machine developments in the LHC [20] and preliminary analysis regarding their influence on corrections and amplitude detuning has been conducted [21]. A new and flexible version of the correction principle has been implemented, taking both optics into account and hence not relying on symmetry assumptions. Extensive tracking studies have been performed, comparing the single- and combined-optics corrections. The results are presented in this paper.



(a) β^*=15 cm round optics (b) β^*=7.5/30 cm flat optics

Figure 1: HL-LHC β-functions in the IR around IP1.

CORRECTION PRINCIPLE

Following the correction procedure as decribed in [10], the RDT to correct is calculated at a point just outside of the IR. Zero and π phase-advances are assumed within one side of the IP and between the two sides respectively:

$$f_{jklm}^{IR} = \int_{IR} \Re\Big[(K_n(s) + iJ_n(s)) i^{l+m} \beta_x(s)^{\frac{j+k}{2}} \times \beta_y(s)^{\frac{l+m}{2}} e^{i\pi n \theta(s-s_{IP})} \Big] ds \overset{\text{correction}}{=} 0 \,, \tag{1}$$

where K_n and J_n are the normal and skew magnetic field strengths of order $n = j + k + l + m$ and $\theta(x)$ being the Heaviside step function. Unlike previous implementations, the RDTs to correct are not hard-coded but can be provided by the user. To correct the other beam, the assumption $\beta_x(s)^{\text{Beam 1}} = \beta_y(s)^{\text{Beam 2}}$ has been made, which is equivalent to exchanging the exponents of β_x and β_y in Eq. (1) and will be indicated in this paper as f_{jklm*}. Taking into account beam direction, the condition $f_{jklm*}^{Beam1} = f_{lmjk}^{Beam2}$ is true for even n , in which case f_{jklm} and f_{lmjk} can be corrected for both beams. These assumptions are strictly speaking only true for perfectly symmetric optics. The new correction implementation overcomes this problem by solving Eq. (1) for both optics at the same time. As only two correctors

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Table 1: Simulation Setup

Machines	**LHC**	**HL-LHC**
Beams	1 and 2	1 and 2
Energy	6.5 TeV	6.5 TeV
β^*	round: 30 cm, flat: 60/15 cm	round: 15 cm, flat: 7.5/30 cm
Combined Optics RDTs	$F_{0003}\, F_{1002}\, F_{3001}\, F_{4000}\, F_{0006}$	$+ F_{0005}\, F_{5000}\, F_{5001}$
Single Optics RDTs	$+ F_{0003^*}\, F_{1002^*}\, F_{1003}\, F_{0004}\, F_{6000}$	$+ F_{0005^*}\, F_{5000^*}\, F_{1005}$
Magnetic Field Errors	$a_3, b_3, a_4, b_4, a_5, b_5, a_6, b_6, a_7, b_7, a_8, b_8$ from 60 WISE-Seeds	
DA-Tracking	100.000 turns 2σ - 30σ in 2σ steps	11 angles $\Delta p/p = 2.7 \cdot 10^{-4}$

Table 2: Orbit Setup. The Values are Given for Beam 1 Round Optics. The Magnitude of the Values are the Same for Beam 2, but Signs Depend on the Orbit-symmetries. In LHC Flat Optics the Crossing Planes are Switched in IP1 and IP5

			IP1		**IP2**		**IP5**		**IP8**	
			H	**V**	**H**	**V**	**H**	**V**	**H**	**V**
LHC	Crossing	[µrad]	–	160	–	200	160	–	-250	–
	Separation	[mm]	-0.55	–	1.4	–	–	0.55	–	-1.0
HL-LHC	Crossing	[µrad]	–	250	–	170	250	–	-200	–
	Separation	[mm]	0.75	–	-1.0	–	–	0.75	–	-1.0

per order and IR are present, only one RDT per beam can be perfectly corrected. Optimization of an overdetermined system would also be possible with the new implementation, but has not been performed in the scope of this study.

SIMULATION SETUP

To compare the effects of different correction methods on the dynamic aperture (DA), the optics, errors and corrections were first set up from within the cpymad [22] wrapper of MAD-X [22] and then tracking studies were performed via SixTrack [23] within the SixDesk [24] environment from the resulting configurations.

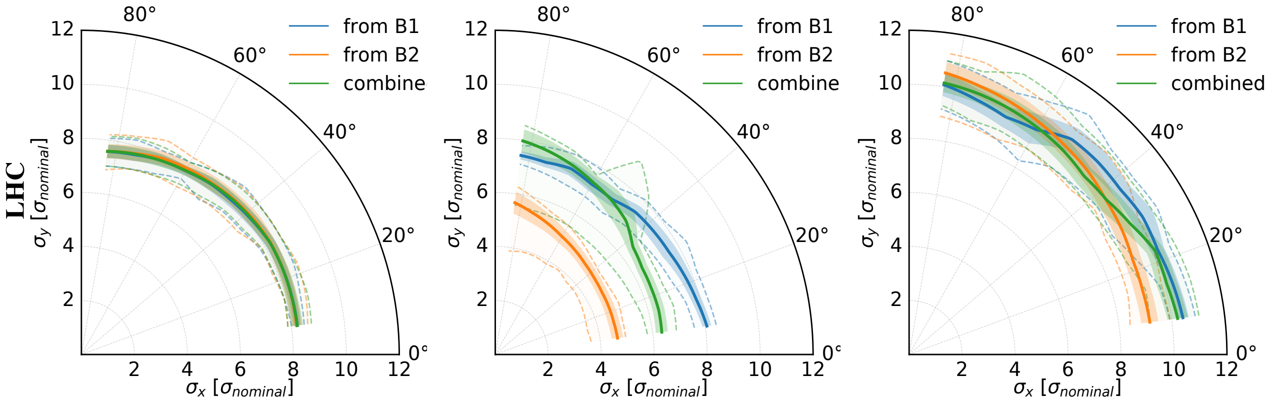
The machines are initialized in MAD-X by loading their sequence and application of the optics of interest: Round optics were utilized with $\beta^*_{x,y} = 30\,\text{cm}$ and $\beta^*_{x,y} = 15\,\text{cm}$ for the LHC and HL-LHC respectively. The investigated flat optics were $\beta^*_x = 60\,\text{cm}$, $\beta^*_y = 15\,\text{cm}$ (in IP1, switched planes in IP5) in the LHC and $\beta^*_x = 7.5\,\text{cm}$, $\beta^*_y = 30\,\text{cm}$ (in IP1, switched planes in IP5) in the HL-LHC. Afterwards one of 60 realizations of the magnetic field errors from the 2015 WISE [25, 26] tables, based on the magnetic measurements mentioned in the introduction, was applied to skew and normal fields, from sextupole to hexadecapole order. A conservative systematic $b_6 = -4$ value was assumed for the HL-LHC. Either of the *single* beam optics or both beam optics *combined* were then chosen to compute the corrections. The RDTs utilized for the corrections can be found in Table 1. "+" indicates that these RDTs were corrected in addition to the ones specified before. In the HL-LHC, three additional RDTs can be corrected, as there are three extra orders of correctors (a_5, b_5 and a_6 [27]) planned to be installed. Feed-down was included into the corrections up to second order on the transverse displacements. After a final coupling correction and matching of the tunes, the resulting configuration was passed to SixDesk, which generates the initial conditions for the particles to be tracked by SixTrack: The particles were evenly distributed over 11 angles in one quadrant of the $x - y$ plane and from 2σ to 30σ in buckets of 2σ in amplitude (all values given in σ of the nominal beam). Within each bucket, 60 particles were initialized, with a relative momentum deviation of $2.7 \cdot 10^{-4}$, and being tracked for 100'000 turns. Survival or loss of these particles determines whether the point was counted as stable or unstable. The minimum DA could then be derived per angle and seed. An overview of the simulation parameters are found in Tables 1 and 2.

RESULTS

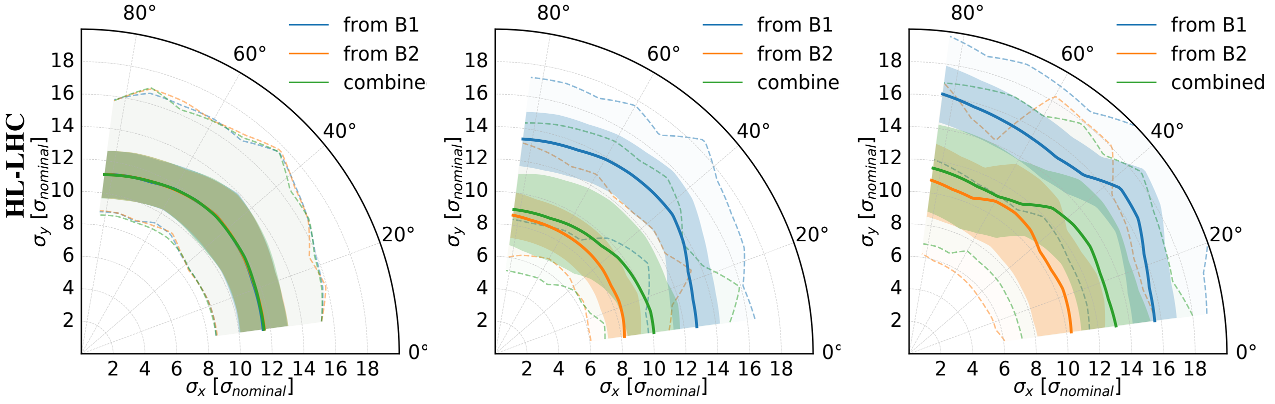
Results of simulations with Beam 1 are shown in the DA plots in Fig. 2, with the statistics over the error realizations: the thick lines show the mean DA, the standard deviation is indicated by the area surrounding it and the dashed lines mark the extrema. LHC simulation results are presented in the top row (Figs. 2a to 2c) while the bottom row (Figs. 2d to 2f) shows HL-LHC results.

As seen from the first column (Figs. 2a and 2d), in case of flat optics without including feed-down into Eq. (1), the corrections as calculated from the other beam optics (orange) are performing as well as the ones calculated from the same beam optics (blue) and from both optics combined (green). This confirms the findings of the preliminary study in [21]. Omitted here are the results from round optics without feed-down, which also show identical DA for all three corrections; this is not surprising, as the symmetry considerations were made for exactly this case.

Including feed-down, the symmetry assumptions break. While for the LHC round optics (Fig. 2c) the split does not favour either correction in Beam 1, it follows the tendencies



(a) LHC flat optics w/o feed-down (b) LHC flat optics w/ feed-down (c) LHC round optics w/ feed-down



(d) HL-LHC flat optics w/o feed-down (e) HL-LHC flat optics w/ feed-down (f) HL-LHC round optics w/ feed-down

Figure 2: DA results for the LHC (top) and HL-LHC (bottom) Beam 1 after applying the corrections from the same beam optics ('from B1', blue), the other beam optics ('from B2', orange), and from both optics combined (green). The thick line indicates the mean over the realizations, while the dashed lines show extrema and the area covers one standard deviation.

of the other three cases in Beam 2 (not shown), which is more pronounced: Correcting via the other beam's optics results in a much worse DA (orange) than the corrections from the beams own optics (blue). Including both beams into the correction can recover some of the lost performance (green), especially in the LHC. The difference between LHC and HL-LHC round optics might stem from the additional correctors in the HL-LHC, which improve the feed-down correction for the same beam, yet add more invalid corrections for the other beam. Not shown here are the results of Beam 2, as they display the same behaviour if not otherwise specified.

When including feed-down into the correction, the best correction for both beams is therefore calculated from both beam optics. While incorporation of feed-down could be beneficial for the correction of a single beam, as seen in Figs. 2d and 2e, the overall correction of both beams was always negatively impacted.

CONCLUSION AND OUTLOOK

Extensive tracking simulations have been performed to investigate how much influence the breakdown of the symmetry considerations utilized in the non-linear corrections of beam optics has on the common correction of both beams in the LHC and HL-LHC. While it has been assumed that the use of flat optics will deteriorate the correction on the other beam, this is not the case. Only when feed-down is considered in the correction scheme we can see a split between the effectiveness of the corrections, as calculated from the optics of the other beam, which can be partly compensated by using both beam optics to compute the correction. In the LHC, this behaviour can be observed only with flat optics, while in the HL-LHC both flat and round optics are affected.

Future studies including feed-down corrections, e.g. as described in [17], can profit from combined optics corrections. Trying to optimize corrections for both beams with additional RDTs might also lead to further improvements.

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