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CORRECTIONS OF FEED-DOWN OF NON-LINEAR FIELD ERRORS IN LHC AND HL-LHC INSERTION REGIONS*†

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Abstract

The optics in the insertion regions of the LHC and its upgrade project the High Luminosity LHC (HL-LHC) are very sensitive to local magnetic errors, due to the extremely high beta-functions present. In collision optics, the non-zero closed orbit in the same region leads to a "feed-down" of high-order errors to lower orders, causing additional effects detrimental to beam lifetime. An extension to the proven method for correcting these errors by locally suppressing resonance driving terms has been undertaken, not only taking this feed-down into account, but also adding the possibility of utilizing it such that the powering of higher-order correctors will compensate for lower order errors. The impact of these corrections on measures of particle stability, namely dynamic aperture and amplitude detuning are presented in this contribution.

INTRODUCTION

The effect of feed-down occurs whenever a particle beam is passing off-center through a magnet, due to either a transverse misalignment of the magnet or an off-center closed orbit of the beam itself. In these cases, the beam will experience magnetic field components created by fields of higher order with identical geometry as lower order fields, which can be understood by a first-order Taylor expansion in Δx and Δy around the zero-orbit. These components cause the same effects on the beam as lower order sources would [1].

The influence of feed-down has been observed and investigated in the insertion regions (IR) of the LHC, where the crossing-angle scheme of the collision optics creates a large orbit bump. For both, LHC and the upcoming High Luminosity LHC (HL-LHC) [2, 3], the need for corrections has been established [4–10].

At the same time, the IRs around the Interaction Points (IPs) 1 and 5 also suffer from an increase in sensitivity to magnetic errors, due to their large β-functions, needed to achieve a low $\beta(s_{IP})$ at the location of the interaction point s_{IP}, referred to as β^*. Installation of additional magnets and the expected decrease of β^* in HL-LHC operation is foreseen to result in even tighter constraints on residual errors. Therefore, correcting the non-linear magnetic errors in these regions has been of significant importance in optimizing the LHC machine performance [6–12]. A useful tool to investigate these errors has been the measurement-based magnetic model [13–15]. While not accurate enough to calculate exact corrections [4], many effects could be studied in simulations and compared to real measurements to predict or confirm beam behaviour, or discover discrepancies [4, 9, 16–18].

To estimate the required strength of the corrector magnets, a local correction scheme based on the knowledge of the Resonance Driving Terms (RDTs) in the IR has been utilized [19]. A new version of the correction principle has now been implemented, allowing among other features to take feed-down into account when calculating the RDTs. To correct the feed-down from higher orders accurately, the calculation is done from highest to lowest RDT order and including the evaluated corrector strengths into the subsequent feed-down. Extensive tracking studies have been performed, investigating the influence of feed-down on the correction and therefore on machine performance. The results are presented in this paper.

CORRECTION PRINCIPLE

Based on the correction principle from [19], the value of the RDT to correct is calculated at a point just outside of the IR. Zero and π phase-advance is assumed within one side and between the sides of the IP, respectively. Including feed-down from the orbit x, y (highlighted in orange), Eq. (1) from [20] transforms into:

$$f_{jklm}^{IR} = \int_{IR} \Re\Bigg[\Bigg(\sum_{q=0}^{\infty}(K_{n+q}(s) + iJ_{n+q}(s))\frac{(x(s)+iy(s))^q}{q!}\Bigg) \times i^{l+m}\beta_x(s)^{\frac{j+k}{2}}\beta_y(s)^{\frac{l+m}{2}}e^{i\pi n\theta(s-s_{IP})}\Bigg]ds \overset{\text{correction}}{=} 0\,, \quad (1)$$

where K_n and J_n are the normal and skew magnetic field strengths of order $n = j+k+l+m$ and $\theta(x)$ is the Heaviside step function. In thin lens approximation [21], Eq. (1) can be expressed as a linear equation system, which can be solved or optimized for the corrector-magnets field strength values.

Correcting f_{4000}, f_{0004}, f_{6000} and f_{0006} will at the same time correct the direct terms of amplitude detuning, which also scale with $\partial Q_z/\partial(2J_z) \propto K_4\cdot\beta_z^2$ and $\partial^2 Q_z/\partial(2J_z)^2 \propto K_6\cdot\beta_z^3$ for first and second order respectively.

SIMULATION SETUP

The effects of including feed-down in the optimisation of machine performance were investigated in tracking simulations and evaluated by their influence on the dynamic aperture. Optics, errors and corrections were first set up from cpymad [22], a python interface to MAD-X [23], and

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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^*	30 cm	15 cm
RDTs	F_{0003} F_{1002} F_{3001} F_{4000} F_{0006} F_{0003^*} F_{1002^*} F_{1003} F_{0004} F_{6000}	as LHC + F_{0005} F_{5000} F_{5001} 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. In Beam 2 the Signs Depend on the Orbit-symmetry

			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

the actual tracking was performed via SixTrack [24] within the SixDesk [25] wrapper from the resulting configurations.

The machines were set-up in MAD-X as summarized in Table 1. The sequence for the respective machine was loaded and optics with $\beta^*_{x,y} = 30$ cm in the LHC and $\beta^*_{x,y} = 15$ cm in HL-LHC were initialized. The orbit was set to either the full crossing scheme (see Table 2) specific to the respective machine or flat-orbit, i.e. crossing and separation set to zero in all IRs. In the latter case, no feed-down effects are present and hence this case can be used as reference for optimal feed-down compensation. Then, one of the 60 realizations of the magnetic model from 2015 WISE [26, 27] tables, was applied to skew and normal fields from sextupole to hexadecapole order. In the RDTs used for correction, "$*$" refers to RDTs with switched β-exponents in Eq. (1) to correct for the other beam [20]. 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 [28]) planned to be installed. Feed-down was calculated up to the second order, when included into the correction. Finally, coupling was minimized and the tunes were matched. The SixDesk environment generated the initial conditions for the particles to be tracked by SixTrack from the resulting machine setup. For the tracking, simulated 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. Within each bucket, 60 particles were initialized with a relative momentum deviation of $2.7 \cdot 10^{-4}$ and were tracked for 100'000 turns.

Survival or loss of these particles determines whether the point was counted as stable or unstable and the minimum DA could then be determined per angle and seed. In the DA plots shown (Figs. 1a and 1d), we can find therefore the results of the simulations with the statistics over the seeds: the mean DA is presented as a thick line, the standard deviation as the area surrounding it and the extrema by dashed lines.

Amplitude detuning to first and second order in amplitude is evaluated via the polymorphic tracking code [29] module in MAD-X and the violin plots of Figs. 1b, 1c, 1e and 1f show again the statistics of the simulation results: the mean and extreme values appear as vertical bars in the plots, while the distribution (kernel density estimation) is given by the colored area, of which one standard deviation is highlighted. As we want to correct the absolute value of the detuning, the results are presented as the change in detuning magnitude before and after correction.

RESULTS

Representative simulation results are shown in Fig. 1. For brevity only Beam 1 is shown, but very similar results were also obtained for Beam 2. As expected, the DA results summarised in the first column (Figs. 1a and 1d), show that the flat-orbit scenario (blue) delivers the best performance, compared to the scenarios introducing the crossing scheme and therefore feed-down effects into the machine. Not taking these effects into account, lowers the DA in both machines by about 3σ (orange). Calculating the corrections according to Eq. (1) with feed-down (green), recovers some of the performance in the HL-LHC simulations. In the LHC setup, the DA is much less affected. It deteriorates even slightly for Beam 2 (not shown).

Looking at improvements of the first and second order amplitude detuning of the two machines (Figs. 1b, 1c, 1e and 1f), we see that in the LHC the correction performs much better when including feed-down. One could see from residual detuning (not shown, due to space limit), that including feed-down corrects closer to the values of the error-free machine and also, that in general the direct terms are better corrected than the cross terms. In the HL-LHC the bulk of the corrections improve the detuning similarly.

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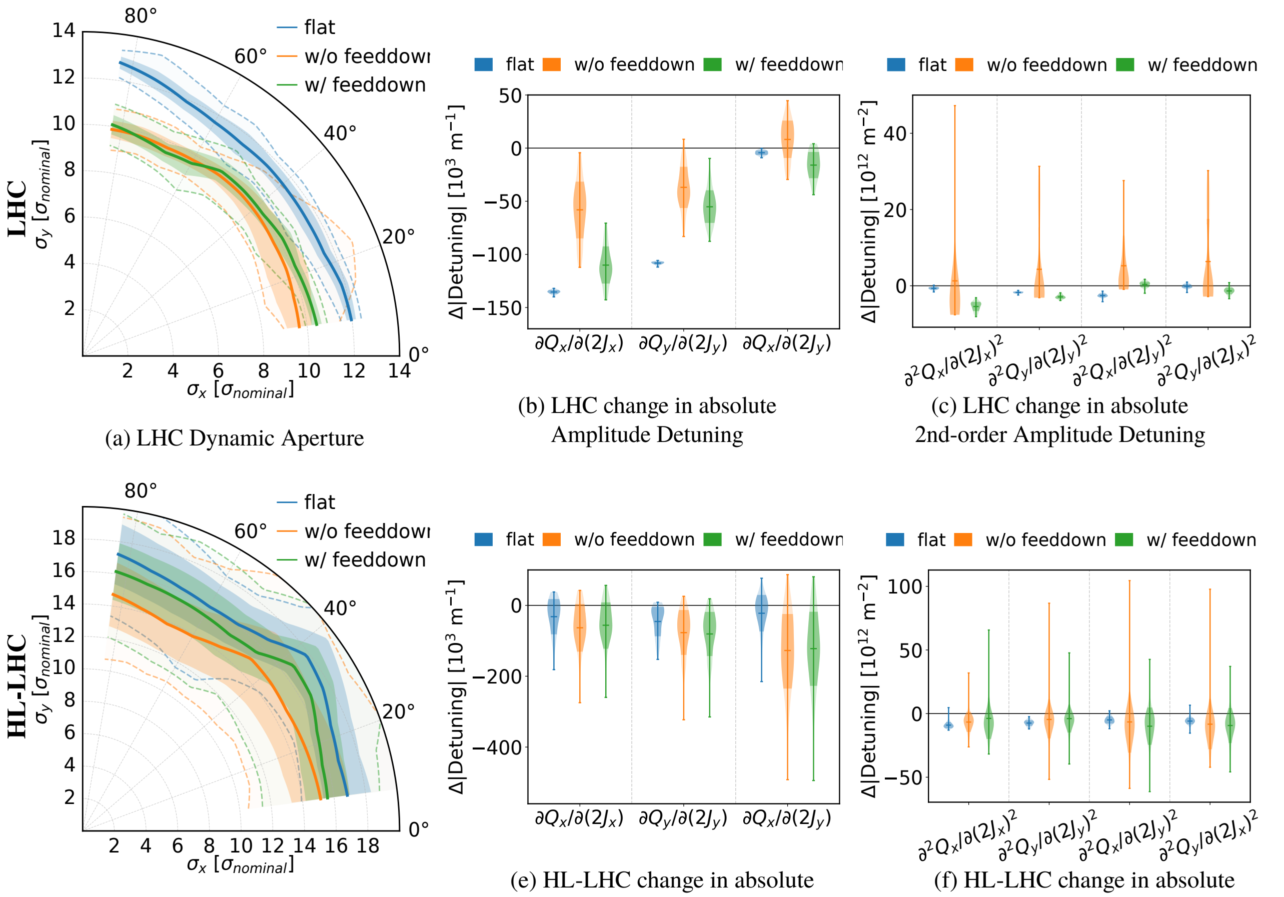

(a) LHC Dynamic Aperture

(b) LHC change in absolute Amplitude Detuning

(c) LHC change in absolute 2nd-order Amplitude Detuning

(d) HL-LHC Dynamic Aperture

(e) HL-LHC change in absolute Amplitude Detuning

(f) HL-LHC change in absolute 2nd-order Amplitude Detuning

Figure 1: Simulation results for LHC (top) and HL-LHC (bottom) after correction. The scenarios are flat orbit (blue), or the full crossing scheme applied and ignoring feed-down in the corrections (orange) or including feed-down into the calculations (green). The statistics over the error realizations are shown by their mean (thick line/central horizontal bar) one standard deviation ([strong] colored area) and extrema (dashed lines/horizontal end-bars). The shape of the violins shows the distribution.

The simulations have been shown to be very sensitive to coupling in the setup. As the coupling is only compensated after correction but the detuning is taken as the difference between before and after applying the correction, the outliers might be explained by the uncorrected coupling in the machine. Further investigations need to be performed. The differences between LHC and HL-LHC behaviour are also not yet understood.

CONCLUSION AND OUTLOOK

The incorporation of feed-down into simulation based RDT optics corrections in the IRs of the LHC and HL-LHC has been investigated through extensive tracking simulations. While no significant impact on DA in the LHC is observed, there are good indications that first and second order amplitude detuning corrections will profit from considering feed-down effects in the calculation of corrections. On the contrary, in the HL-LHC a clear improvement is seen on the DA when considering the feed-down, but no improvement is seen in the amplitude detuning. These results should be taken with caution, as the corrections are done on magnets common to both beams, and the influence on the other beam is neglected for the scope of this paper. It has been shown, that the DA of the other beam deteriorates when feed-down is factored in, as its influence can be opposite between beams [20].

Further studies are planned employing the new correction implementation, for example to correct the amplitude detuning cross terms via f_{2020}. Preliminary studies have been conducted utilizing the feed-down from dodecapole correctors to correct the octupole fields. These show promising results, as they seem to correct first and second order amplitude detuning simultaneously, which will be presented in a future publication.

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