# SPECIFICATION OF A SYSTEM OF CORRECTORS FOR THE TRIPLETS AND SEPARATION DIPOLES OF THE LHC UPGRADE*

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*Abstract*

The luminosity upgrade of the LHC aims at reducing beta* from 55 cm to 15 cm or beyond. This can be achieved by the ATS [1] scheme and means of new large aperture superconducting triplet (IT) quadrupoles (150 mm), preferably using the $Nb_3Sn$ technology in order to keep the gradient reasonably high (140 T/m). The field quality requires careful specification in order to ensure a large enough dynamic aperture (DA). In this context, dedicated corrector magnets are foreseen to provide semi-local corrections of specific multipole components and find the best possible compromise between the demand and what can be realistically achieved by the magnet manufacturer. In this paper the layout and main parameters of the IT corrector package are presented together with the correction strategy. Moreover, the foreseen performance is discussed in detail.

## CORRECTOR LAYOUT AND STRATEGY

The correction strategy follows the one which was established for correcting the field imperfections of the existing triplet and D1 [2, Section 2.2]. The basic principles of the method are described below, with its extension to new multipoles such as $a_5$, $b_5$ and $a_6$ for which no correction is presently available in the nominal LHC.

On either side of the interaction point (IP) of the low-$\beta$ insertion, generally in between the inner triplet and D1 where the $\beta$ functions are substantially different in both planes, a dedicated correction coil is installed for each multipole component which is found to be critical for the DA. For the latest version of the HL-LHC optics and layout [3], as for previous versions, the multipole correctors of the triplet and D1 are combined in a corrector package installed on the non-IP side of Q3 which contains all multipole correctors, normal and skew, up to order $n = 6$, except $b_2$ (see Fig. 1). For a given normal or skew field imperfection $B_n^{\pm}(s)$ ($n = 2, 3, \ldots$ for quadrupole, sextupole, …), generally varying from magnet to magnet, the correction consists in cancelling one or several resonance driving terms, as seen both by the clock- and counter-clock wise beams, Beam1 and Beam2:

$$c_{1,2}^{\pm}(n; p, q) \stackrel{\text{def}}{=} \int_{\text{IR}} B_n^{\pm}\, \beta_{x_{1,2}}^{\frac{|p|}{2}}\, \beta_{y_{1,2}}^{\frac{|q|}{2}}\, e^{i\left(p\mu_{x_{1,2}} + q\mu_{y_{1,2}}\right)}, \quad (1)$$

where $p$ and $q$ are integer such that $|p| + |q| = n$, $q$ is even (resp. odd) in the case of normal (resp. skew) multipole. The field integral above is taken over the most critical magnets of the interaction region (IR), namely the two triplets

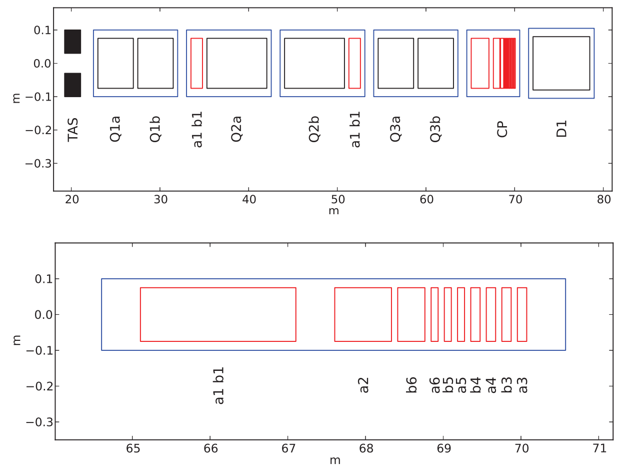


Figure 1: Upper: Sketch of the latest HL-LHC IT and D1 layout with associated correctors [3]. Lower: zoom of the triplet corrector package. The horizontal scale indicates the distance to the IP.

and D1s, and the multipole corrector magnets themselves, and is weighted by the beta-functions $\beta_{x_{1,2}, y_{1,2}}$. For sufficiently low $\beta^*$ (typically below 1 m for the LHC), the betatron phase advances are almost constant on a given side of the IR and jump by $\pi$ from left to right. Assuming that the $\beta$-beating is well controlled for each beam separately, a certain number of optics relations, valid for both round and flat configurations, can be established, linking the beta-functions of the two beams, e.g. $\beta_{x_2}(s) = \beta_y^*/\beta_x^* \times \beta_{y_1}(s)$, and conversely exchanging $x$ into $y$. Therefore, it is sufficient to consider one beam only and, for each multipole, adjust the strength of the two corresponding corrector magnets to cancel selectively at most two of the following quantities:

$$\kappa_{n,p,q}^{\pm} \stackrel{\text{def}}{=} \int_{\text{Left}} B_n^{\pm}\, \beta_x^{\frac{|p|}{2}}\, \beta_y^{\frac{|q|}{2}} + (-)^n \int_{\text{Right}} B_n^{\pm}\, \beta_x^{\frac{|p|}{2}}\, \beta_y^{\frac{|q|}{2}}, \quad (2)$$

with $|p|+|q| = n$, and at least one of $p, q$ is even (resp. odd) for normal (resp. skew) multipoles.[1] For reasons related to the distance of the LHC working point to the closest resonances (e.g. 3rd order for the sextupole and dodecapole imperfections), but also to reduce the DA variation vs. the azimuthal angle in physical space, the following selection of driving terms has been implemented in the correction algorithm: $\kappa_{2,1,1}^-$ and ($\kappa_{4,1,3}^-$, $\kappa_{4,3,1}^-$) for $a_2$ and $a_4$ field imperfections, respectively; then ($\kappa_{3,1,2}^+$, $\kappa_{3,2,1}^+$) for $b_3$, ($\kappa_{3,3,0}^-$, $\kappa_{3,0,3}^-$) for $a_3$, ($\kappa_{4,4,0}^+$, $\kappa_{4,0,4}^+$) for $b_4$, ($\kappa_{5,5,0}^{\pm}$, $\kappa_{5,0,5}^{\pm}$) for $a_5$ and $b_5$, ($\kappa_{6,6,0}^+$, $\kappa_{6,0,6}^+$) for $b_6$, and ($\kappa_{6,5,1}^-$, $\kappa_{6,1,5}^-$) for $a_6$.

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[1] The suffix 1 or 2 identifying the beam in Eq. (1) has been removed for clarity.

Concerning the other $\kappa^{\pm}$ factors, simulations show they are at least reduced by one order of magnitude when the source of imperfection is systematic from magnet to magnet, and by factors of at least 2 to 3 when the source is random. The field imperfections induced by feed-down effects from the crossing angle are also strongly minimised. Indeed the closed orbit excursion in the IR evolves $\simeq \sqrt{\beta}$ in the crossing plane. As a result, the corresponding $\kappa^{\pm}$ factors are proportional to those directly induced by the multipole field imperfections of higher order that are the source of the generated lower orders.

## CORRECTORS' SPECIFICATION

### *Strength*

The specification of the strength requirements for the non-linear correctors in the proposed IT has been performed by means of numerical simulations. The algorithm presented in the previous section has been applied to sixty different realisations (also called seeds) of the magnetic field errors of the triplets and the superconducting D1 separation dipoles. Therefore, the correctors' strength depends on the target field quality of the new triplets, but also of the new separation dipoles. The estimate of the new triplet and D1 field quality used in the numerical simulations is reported in Table 1 and 2, respectively. Such target error

Table 1: Multipoles Used for the Field Quality of the Triplets. The Values are in Units of $10^{-4}$ at $R_{ref} = 50$ mm.

| | | Mean | Unc. | Random |
|---|---|---|---|---|
| normal | 3 | 0.000 | 0.820 | 0.820 |
| | 4 | 0.000 | 0.570 | 0.570 |
| | 5 | 0.000 | 0.420 | 0.420 |
| | 6 | 0.800 | 1.100 | 1.100 |
| skew | 3 | 0.000 | 0.800 | 0.800 |
| | 4 | 0.000 | 0.650 | 0.650 |
| | 5 | 0.000 | 0.430 | 0.430 |
| | 6 | 0.000 | 0.310 | 0.310 |

tables have been provided by the HiLumi WP3 in November 2012 [4, 5]. It is worth recalling that in the framework of the LHC studies the magnetic errors are split into three components, namely a mean ($S$), uncertainty ($U$), and random ($R$) such that a given multipole is obtained by

$$b_n = b_{n_S} + \frac{\xi_U}{1.5}\, b_{n_U} + \xi_R\, b_{n_R}, \qquad (3)$$

where $\xi_U, \xi_R$ are Gaussian distributed random variables cut at 1.5 $\sigma$ and 3 $\sigma$, respectively. The $\xi_U$ variable is the same for all magnets of a given class, but changes from seed to seed and for the different multipoles. On the other hand, $\xi_R$ changes also from magnet to magnet. Then, the field expansion for a dipole is given by

$$B_y + i\, B_x = B_{ref} \sum_{n=1}^{N} (b_n + i\, a_n) \left(\frac{x + i\, y}{R_{ref}}\right)^{n-1}. \qquad (4)$$

Table 2: Multipoles Used for the Field quality of the D1 Separation Dipoles. The Values are in Units of $10^{-4}$ at $R_{ref} = 50$ mm.

| | | Mean | Unc. | Random |
|---|---|---|---|---|
| normal | 3 | -0.900 | 0.727 | 0.727 |
| | 4 | 0.000 | 0.126 | 0.126 |
| | 5 | 0.000 | 0.365 | 0.365 |
| | 6 | 0.000 | 0.060 | 0.060 |
| skew | 3 | 0.000 | 0.282 | 0.282 |
| | 4 | 0.000 | 0.444 | 0.444 |
| | 5 | 0.000 | 0.152 | 0.152 |
| | 6 | 0.000 | 0.176 | 0.176 |

The estimated correctors' strengths on the left and right side of the two high-luminosity insertions IR1 and 5 have been combined into histograms with 240 entries. The resulting distributions are shown in Fig. 2, where the normal and the skew correctors are represented in blue and red, respectively. Rather symmetric distributions are observed and, while in general the width of the distribution does not change between corresponding normal and skew correctors, a large difference is observed in the case of the $a_6$ corrector. In the study, the sensitivity of the final correctors' strength on the assumed field quality of the D1 magnet has been assessed. Indeed, by assigning field errors to the separation dipoles only, the strength of the correctors of order 3 and 5, which are allowed components for dipoles, are a factor of 3-4 smaller than in the case of errors in both triplets and separation dipoles. On the other hand, the higher-order correctors are completely negligible in terms of strength whenever only the separation dipoles have magnetic field errors assigned.

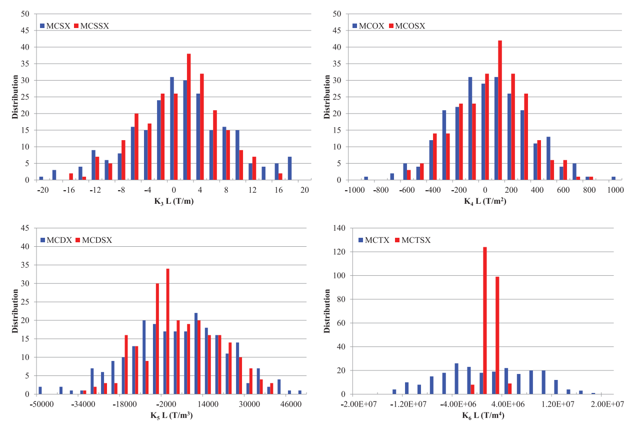


Figure 2: Distribution of the strength of the non-linear correctors: $a_3, b_3$ (upper left); $a_4, b_4$ (upper right); $a_5, b_5$ (lower left); $a_6, b_6$ (lower right).

The maximum strength obtained from the numerical simulations including both triplets' and separation dipoles' field errors are listed in the first column of Table 3. The agreed specification is given in the second column, with a safety margin ranging between 1.5 and 2.

It is worth emphasising that in the same Table 3 the specification of the skew quadrupole corrector has been in-




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cluded to ensure the full correction of a roll angle error of ±3 mrad (1 mrad rms) for the inner triplet.

Table 3: Strength of the Triplet Correctors.

| | | Computed mT m at 50 mm | Specification mT m at 50 mm |
|---|---|---|---|
| normal | 3 | 31.2 | 63 |
| | 4 | 22.9 | 46 |
| | 5 | 16.9 | 25 |
| | 6 | 57.3 | 86 |
| skew | 2 | 500.0 | 1000 |
| | 3 | 26.3 | 63 |
| | 4 | 18.8 | 46 |
| | 5 | 11.7 | 25 |
| | 6 | 11.2 | 17 |

### *Performance*

The performance of the proposed non-linear correctors has been assessed on the basis of numerical simulations of the dynamic aperture (DA) of the whole machine. To this aim the so-called SLHCV3.1b layout [6], with a triplet gradient of 150 T/m, has been used and several configurations considered, namely with or without the full correction system, with one single corrector not used, and an intermediate configuration in which the correctors corresponding to $a_5, b_5, a_6$ are not used. The last configuration allows checking the need for these correctors that are not installed in the nominal LHC. The results are given in Fig. 3, where the DA for 59 phase space angles, 60 seeds, $10^5$ turns is shown. The field errors are assigned to all magnets in the arcs and IRs based on the data of the magnetic measurements. For the high luminosity insertions only the triplets' errors are assigned with components from order 3 to 14. The markers represent the average DA (over the seeds and the angles), while the negative error bars represent the minimum DA (over the seeds and the angles) and the positive error bars the average DA over the angles of the maximum over the seeds. In this way the spread introduced by the realisations and the phase space angles is made visible in a compact form. In the upper plot the impact of each individual corrector is shown. While the average DA is affected only by the $b_6$ corrector, the error bars reflect an impact also of the low-order normal correctors, while the skew correctors are less relevant, in particular $a_5, a_6$. In the lower plot the overall effectiveness of the non-linear correction system (about 5 $\sigma$ gained for both average and minimum DA) is clearly visible. Furthermore, the positive impact of the $a_5, b_5, a_6$ correctors is also seen, with an improvement of 1.5 $\sigma$ for the average DA and more than 3 $\sigma$ for the minimum one.

## CONCLUSIONS AND OUTLOOK

A non-linear correctors' system has been devised for the HL-LHC machine. The detailed specification of the layout and strength of the correctors has been given. Furthermore, the actual performance in terms of increase of DA has been assessed for the so-called SLHCV3.1b layout, showing a very positive impact of the proposed system, which is now in the baseline of the official HL-LHC layout.

The system will be re-assessed for the latest version of HL-LHC[3], but no major changes are to expected.

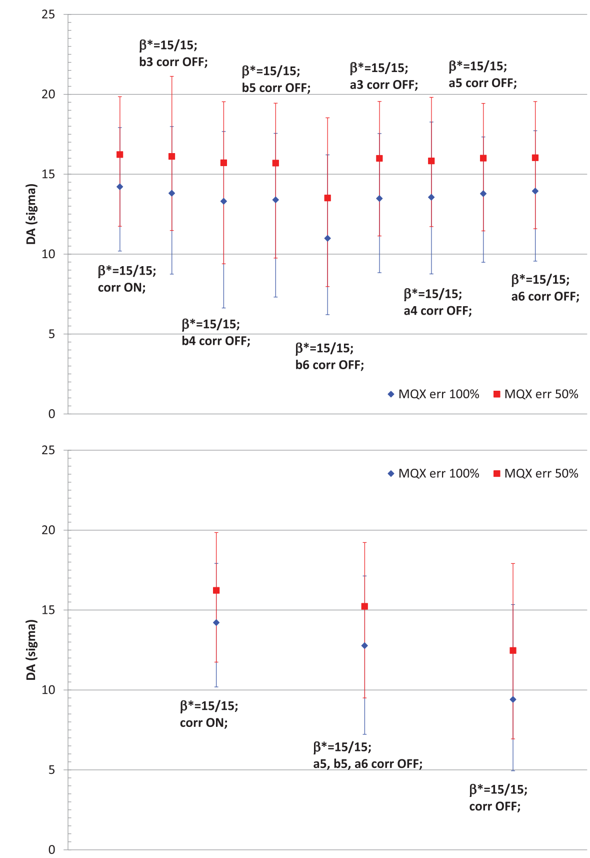


Figure 3: Impact of the absence of one corrector on the dynamic aperture (upper). Impact of the absence of groups of correctors on the dynamic aperture (lower). The blue series refers to simulations performed with the full multipoles from Table 1, while the red one refers to simulations performed with 50 % of the multipoles.

## ACKNOWLEDGEMENTS

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