SPECIFICATION OF FIELD QUALITY IN THE INTERACTION REGION MAGNETS OF THE HIGH LUMINOSITY LHC BASED ON DYNAMIC APERTURE [*] [†]

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Abstract

New large aperture Inner Triplet quadrupoles, separation dipoles and the nearby matching quadrupoles will be installed in the low-beta interaction regions (IR) of the high luminosity LHC upgrade (HL-LHC) [1]. The large aperture is necessary for accommodating the increased beam size due to much higher beta functions in these magnets for the low β^* collision optics. The high beta functions will amplify the effects of field errors in the new magnets leading to a smaller dynamic aperture (DA). It is, therefore, critical to evaluate the impact of these errors on the DA and specify the magnet field quality (FQ) satisfying an acceptable DA while being realistically achievable. The study is performed for the HL-LHC lattice layouts SLHCV3.1b and HLLHCV1.0 for collision and injection energies.

INTRODUCTION

The beta-functions at the Interaction Points (IP) of the high luminosity LHC upgrade lattice (HL-LHC) [2] at collision energy will be significantly lower than in the nominal LHC. Consequently, the β-values in the Inner Triplet (IT) and the nearby magnets will be much higher. To accommodate the resulting larger beam size at these locations, new large aperture magnets will be installed in the experimental insertions IR1 and 5 [3]: the Nb_3Sn superconducting (SC) IT quadrupoles with 150 mm coil aperture, Nb-Ti SC separation dipoles D1 and D2 with 160 mm and 105 mm aperture, respectively, SC Q4 quadrupoles with 90 mm aperture, and longer Q5 quadrupoles with 70 mm aperture (see magnet development in Refs. [3–8]). The high beta-functions will amplify beam distortions caused by field errors in these magnets, leading to a smaller dynamic aperture (DA). A sufficiently large DA is necessary for an efficient injection and long beam lifetime. It is, therefore, crucial to evaluate the field error effects of the new magnets on the DA and specify realistically achievable FQ satisfying an acceptable DA.

The IT FQ has been previously optimized for the SL-HCV3.01 lattice at collision energy of 7 TeV [9], and the initial evaluation of error effects of the D1, D2, Q4, Q5 magnets was performed [10]. This study is extended to the more recent lattices SLHCV3.1b [3] and HLLHCV1.0 [2] for both collision and injection energies.

The DA was obtained in SixTrack [11, 12] tracking simulations with the following set-up: 10^5 turns, 11 x-y phase space angles, 30 particle pairs per 2σ amplitude step, 60 random error seeds, normalized emittance of 3.75 μm, $\Delta p/p = 2.7 \cdot 10^{-4}$ and $7.5 \cdot 10^{-4}$ at 7 TeV (collision) and 450 GeV (injection) beam energy, respectively. In the rest of the ring field errors based on measured FQ of the existing magnets were always included. The ring correction systems include correction of tune, chromaticity, coupling and orbit, the b_3, b_4, b_5 correctors in the arc dipoles, as well as the local compensation of the IT and D1 non-linear field errors [13]. The previously used SLHCV3.01 lattice included the IT correctors for compensating a_3, b_3, a_4, b_4, b_6 field errors. It was determined that correctors for a_5, b_5, a_6 terms are also necessary for an adequate DA. They were added in the SLHCV3.1b and HLLHCV1.0 lattices. Additionally, the feed-down effects caused by the curved reference orbit in the straight D1 and D2 dipoles have been implemented, while beam-beam effects are not included.

FIELD QUALITY

The non-linear magnetic FQ of LHC magnets is defined by the following expansion [14]

$$B_y + iB_x = 10^{-4} B_N \sum_{n=N}^{\infty} (b_n + ia_n) \left(\frac{x + iy}{r_0} \right)^{n-1}, \quad (1)$$

where the a_n, b_n coefficients are determined at a reference radius r_0, and B_N is the main field at r_0. Furthermore, each a_n and b_n is composed of the mean (a_{nm}, b_{nm}), uncertainty and random terms, where the uncertainty and random values are randomly generated based on their Gaussian sigmas a_{nu}, b_{nu} and a_{nr}, b_{nr}, respectively (see, e.g., Ref. [13]).

To make sure the FQ specifications for the new magnets are realistic, one can use their field estimates obtained from magnet design and scaling of measured field of the existing magnets as a baseline for the optimization. The previously optimized IT specifications at 7 TeV [9] were updated to take into account the additional IT correctors for a_5, b_5, a_6 errors in the new lattices - hence, the corresponding field terms had been increased by a factor of 2 to 5. These specifications will be referred to as `IT_errortable_v66`. Estimate of the D1 FQ is based on magnet design and referred to as `D1_errortable_v1` [15]. Due to the evolution of the D2 dipole design, three versions of the D2 FQ were used in the study referred to as `D2_errortable_v3, _v4` [16], and `_v5` [17]. The D2 low order terms at 7 TeV in these tables are shown in Table 1. Estimates for the Q4 and Q5 magnets are based on scaling of measured field of the existing

Table 1: Evolution of Low Order Terms of the Estimated D2 FQ at 7 TeV ($r_0 = 35$ mm)

n	a_{nm}	a_{nu}	a_{nr}	b_{nm}	b_{nu}	b_{nr}
			D2_errortable_v3			
2	0.0	0.679	0.679	65.0	3.000	3.000
3	0.0	0.282	0.282	-30.0	5.000	5.000
4	0.0	0.444	0.444	25.0	1.000	1.000
5	0.0	0.152	0.152	-4.0	1.000	1.000
6	0.0	0.176	0.176	0.0	0.060	0.060
			D2_errortable_v4			
2	0.0	0.679	0.679	25.0	2.500	2.500
3	0.0	0.282	0.282	3.0	1.500	1.500
4	0.0	0.444	0.444	2.0	0.200	0.200
5	0.0	0.152	0.152	-1.0	0.500	0.500
6	0.0	0.176	0.176	0.0	0.060	0.060
			D2_errortable_v5			
2	0.0	0.679	0.679	1.0	1.000	1.000
3	0.0	0.282	0.282	1.0	1.667	1.667
4	0.0	0.444	0.444	-3.0	0.600	0.600
5	0.0	0.152	0.152	-1.0	0.500	0.500
6	0.0	0.176	0.176	2.0	0.060	0.060

MQY quadrupole and referred to as `Q4_errortable_v1` and `Q5_errortable_v0`, respectively. All these FQ tables can be found at the official LHC repository on [18, 19].

SLHCV3.1B LATTICE

The SLHCV3.1b collision optics has the same $\beta^* = 15$ cm as SLHCV3.01. The differences include the IT quadrupoles with a higher gradient of 150 T/m at 7 TeV and additional IT correctors for compensating a_5, b_5, a_6 field errors. The feed-down effects caused by orbit in the straight D1 and D2 separation dipoles are now implemented.

The desired minimum DA (among all seeds and phase angles) at collision energy is $\simeq 10\,\sigma$. Tracking with the IT field of `IT_errortable_v66` and without the D1, D2, Q4, Q5 errors results in DA$_{min}$ = 10.38 σ which is acceptable. Hence the IT specifications optimized for the SLHCV3.01 lattice are also valid for the SLHCV3.1b lattice.

As a next step, impact of the D1, D2, Q4, Q5 field errors on the DA was verified. The Q4 and Q5 estimated field errors produced negligible effect on the DA, hence this FQ is acceptable. Impact of the D1 estimated errors is mostly due to the relatively large "allowed" mean terms b_{nm}. Figure 1 shows that the largest DA reduction is caused by b_{7m} and b_{9m} terms. DA$_{min}$ is the minimum DA over 60 seeds, and DA$_{ave}$ is the minimum value of the average DA for all angles. The low order D1 errors have negligible effect since they are compensated by the included IT correctors of order n=3-6. To reduce the impact of the b_{7m} and b_{9m} while keeping them realistic, it is proposed to reduce them by a factor of 2 (to 0.2 and -0.295, respectively) relative to `D1_errortable_v1`.

Two versions of the estimated D2 FQ were used for the SLHCV3.1b tracking: `D2_errortable_v3` and `D2_errortable_v4`. The v3 estimate was obtained for a shorter magnet, hence the b_2-b_4 terms are rather large due
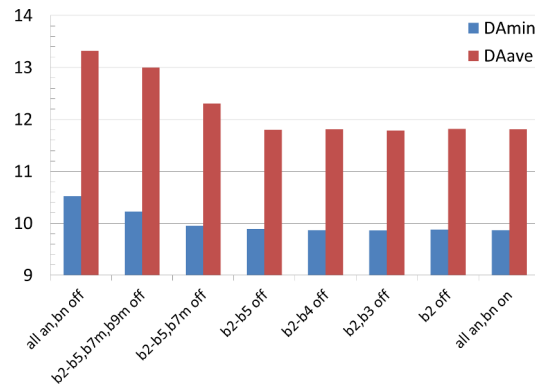

Figure 1: DA vs. D1 FQ for SLHCV3.1b at 7 TeV (with all magnet errors except D2).

to field saturation. These terms showed a strong impact on the DA. The b_2 affected the linear optics by increasing β^*, thus resulting in too optimistic DA. To avoid this effect the b_2 was set to zero in all future tracking, assuming it can be reduced and the IP beta will be corrected. Strong impact of the D2 b_3 is shown in Fig. 2. A large effect is also produced by the b_4. Effects of feed-down due to orbit in the straight D1 and D2 were found very small. To maintain the DA$_{min}$ near 10 σ, the b_3, b_4 terms must be reduced an order of magnitude relative to `D2_errortable_v3`. These terms had been, indeed, much improved in `D2_errortable_v4` update (see Table 1). Following the tracking results, the proposed further adjustment for the _v4 table is to reduce the b_2 to $\simeq 1.0$ and b_{3m} from 3.0 to 1.5. The resulting DA$_{min}$ and DA$_{ave}$ at 7 TeV with all new magnet errors and adjustments are 9.90 σ and 11.64 σ, respectively, which is acceptable.
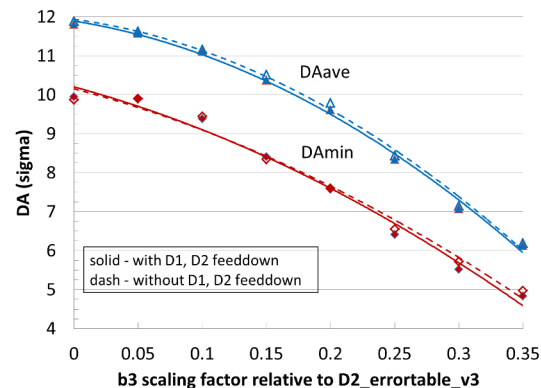

Figure 2: DA vs. b_3 of D2 for SLHCV3.1b at 7 TeV.

The β^* for SLHCV3.1b lattice at 450 GeV is 5.5 m, with a factor of 35 lower peak beta functions in the IR magnets compared to the collision optics. Beam sizes in these magnets are also reduced even though the emittance is a factor of 16 larger. Therefore, the impact of field errors of the new magnets will be much smaller, and the use of the IT correctors is *a priori* not needed. Figure 3 shows very small DA sensitivity to the new magnet field errors. Hence, their FQ at injection based on the present estimates are acceptable. The resulting DA$_{min}$, DA$_{ave}$ with all the errors are 10.16 σ

and 10.53 σ, respectively, and are acceptable. Another option of the injection optics with β^* of 11 m was verified and showed very similar DA.

The injection DA, however, is $\simeq 1\,\sigma$ smaller than the nominal LHC DA. Since it is not limited by the IR magnets, other improvements (e.g. in arcs) may need to be considered. Possible options include a larger integer tune split and adjustment of the working point. Figure 4 shows a tune scan indicating effect of the 7th order horizontal resonance close to the current tune (62.28,60.31). Reducing the x and y tunes by about 0.01 would increase the DA by $\simeq 0.5\,\sigma$.
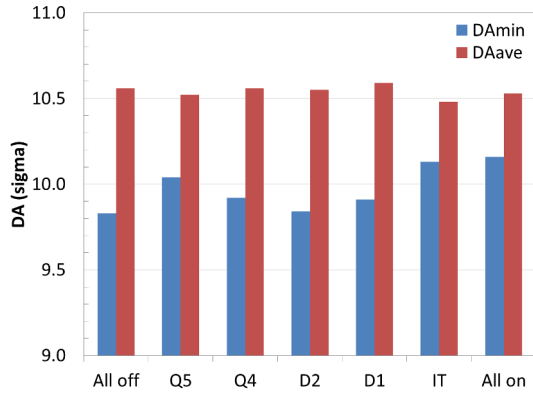

Figure 3: DA vs. FQ of new magnets (turned on one at a time) for SLHCV3.1b at 450 GeV.
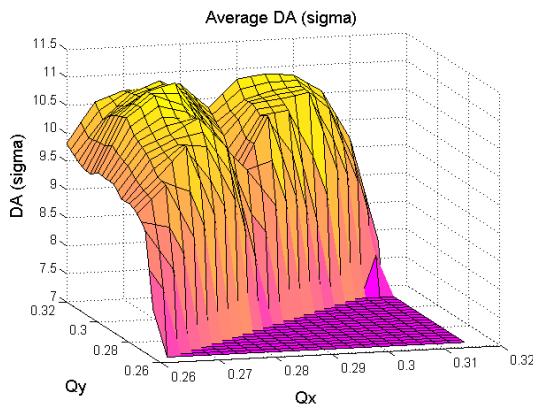

Figure 4: DA vs. tune for SLHCV3.1b at 450 GeV. Tunes below $Q_x = Q_y$ line were not scanned.

HLLHCV1.0 LATTICE

The HLLHCV1.0 is the latest version of the HL-LHC lattice. Some of the differences relative to the SLHCV3.1b include: a longer IT with a lower gradient of 140 T/m and higher peak beta function (7%) at collision, adjusted orientation of magnets in the cryostat, new IT corrector positions, and different phase advance between the IP1 and IP5.

Using the previously optimized FQ of the new magnets, the collision DA of the HLLHCV1.0 lattice is reduced by $\simeq 1\,\sigma$ relative to the SLHCV3.1b to $DA_{min} = 8.83\,\sigma$ and $DA_{ave} = 10.41\,\sigma$. A stronger impact of the D2 b_3 and b_4 terms of the previously adjusted D2_errortable_v4 was

noticed. Since the b_{3m} had been already reduced in this table, the next step to try was to reduce the b_{4m} by half. This improved the DA to $DA_{min} = 9.14\,\sigma$ and $DA_{ave} = 11.07\,\sigma$. Further improvement was achieved when using the most recent D2 field estimate D2_errortable_v5 [17] (see Table 1), where the b_2, b_3 terms are reduced at the expense of somewhat larger higher order terms. In this case, the $DA_{min} = 9.85\,\sigma$ and $DA_{ave} = 12.47\,\sigma$, as shown in Fig. 5, which is acceptable and comparable to the DA of the SLHCV3.1b. The reasons for such noticeable improvement will need to be further analyzed.
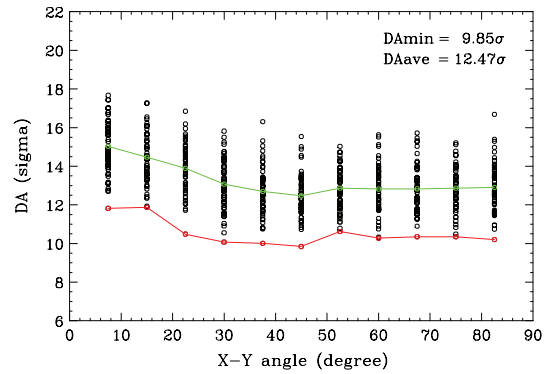

Figure 5: DA of HLHCV1.0 at 7 TeV with adjusted estimated FQ of new magnets.

The β^* at injection for HLLHCV1.0 is 6.0 m, comparable to SLHCV3.1b. Impact of the new magnets field errors on the DA was verified and found insignificant (similar to the SLHCV3.1b). The resulting DA with all errors ($DA_{min} = 9.95\,\sigma$, $DA_{ave} = 10.46\,\sigma$) is acceptable, see Fig. 6.
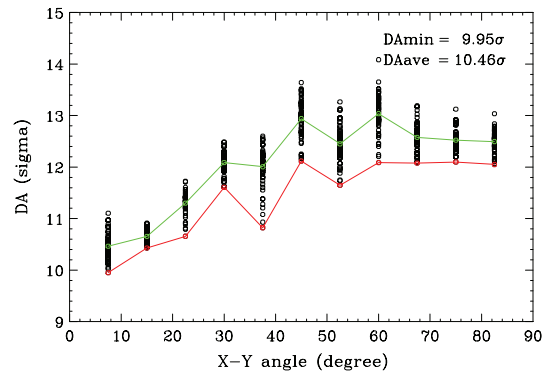

Figure 6: DA of HLLHCV1.0 at 450 GeV with estimated FQ of new magnets.

CONCLUSION

DA evaluation for the SLHCV3.1b and HLLHCV1.0 lattices using the latest FQ estimates for the new large aperture IT, D1, D2, Q4 and Q5 magnets determined that an acceptable DA_{min} of $\simeq 10\,\sigma$ can be reached at both collision and injection energy with small adjustments of the field quality at collision energy. At injection energy, no adjustments are required since the DA is not limited by the new magnets FQ. The injection DA can be further improved ($\simeq 0.5\,\sigma$) by a small adjustment of working point.

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