EVALUATION OF FIELD QUALITY FOR SEPARATION DIPOLES AND MATCHING SECTION QUADRUPOLES FOR THE LHC HIGH LUMINOSITY LATTICE AT COLLISION ENERGY [*] [†]

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Abstract

The high luminosity upgrade of the LHC lattice (HL-LHC) requires new larger aperture magnets to be installed in the low-beta interaction regions (IRs). These include Nb_3Sn superconducting (SC) inner triplet (IT) quadrupoles, Nb-Ti SC separation dipoles D1 and D2, and SC Q4 quadrupoles [1, 2, 3, 4]. The upgrade significantly reduces the β^* functions at these IRs at collision energy [5]. Consequently, beta functions and beam size in these magnets will increase, thus requiring a larger aperture. The high beta functions also increase the impact of high order field errors in these magnets on dynamic aperture (DA). Therefore, to maintain an acceptable DA, the field quality in the new magnets needs to be specified. Since the error effects at collision are dominated by the triplets, their field quality was specified first [6]. Next, the field errors were added to the D1, D2 dipoles and Q4, Q5 matching quadrupoles while keeping the IT errors to specifications. The impact of these errors on DA was determined in tracking simulations using SixTrack [7]. First evaluation of the field quality in the D1, D2, Q4 and Q5 magnets is presented.

INTRODUCTION

The low-beta IR optics (see [5] for the latest version) in the HL-LHC upgrade lattice at collision energy will significantly increase beta functions and beam size in the magnets near the interaction points (IP). This will require installation of new large aperture magnets including: Nb_3Sn SC inner triplet quadrupoles with 150 mm coil aperture, Nb-Ti SC separation dipoles D1, D2 with 160 mm and 105 mm aperture, respectively, SC Q4 matching quadrupoles with 90 mm aperture, and longer Q5 quadrupoles with 70 mm aperture (see specifications in [8] and present hardware development in [1, 2, 3, 4]). The high beta functions will amplify the effects of non-linear field errors in these magnets leading to a smaller dynamic aperture. A large DA is important for an efficient injection and long beam lifetime. Satisfying an acceptable DA requires specification of an adequate field quality in these magnets.

Due to the strongest impact, the IT field quality was studied separately [6]. Next, the field errors were added to the D1, D2, Q4, Q5 magnets while the IT errors were set to the specifications in the IT error table “target65” [6]. The desired field quality in the new magnets must guarantee a sufficient DA and should be realistically achievable.

This study was performed for the HL-LHC layout version SLHCV3.01, where the IT quadrupole gradient is 123 T/m and $\beta^*_{x,y} = 15$ cm at IP1 and IP5. The DA was obtained in SixTrack [7] tracking simulations with 10^5 turns, 11 x-y angles, 30 particle pairs per 2σ amplitude step, up to 60 random error seeds, normalized emittance of 3.75 μm·rad, and $\Delta p/p = 2.7\cdot10^{-4}$ at 7 TeV beam energy. The SLHCV3.01 lattice includes the IT non-linear field correctors for local compensation of the IT and D1 error terms a_3, b_3, a_4, b_4, b_6 [9]. The IT correctors for a_5, b_5, a_6 terms are also planned [9], but were not implemented in this lattice. The D2, Q4, Q5 errors were corrected to low order using the standard ring correction of tune, chromaticity, coupling and orbit. The tracking also included arc errors based on magnetic measurements, and their correction. The current lattice model does not take into account the off-center trajectory in the D1, D2 dipoles, thus missing the feed-down effects. Therefore, the resulting DA should be considered optimistic.

EXPECTED FIELD QUALITY

The magnetic field can be expanded as [10]

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

where a_n, b_n coefficients are in units of 10^{-4} at a reference radius r_0, and B_N is the main field at r_0. In the LHC studies, each of the a_n and b_n is composed of three terms, namely mean (m), uncertainty (u) and random (r), related to systematic and random type errors (see detailed description e.g. in [9]). Below, the a_n, b_n without the m, u, r indexes include all the three terms.

It is logical to start the error evaluation from the expected field quality in the new magnets. The latter can be obtained by either using magnetic field calculations or scaling the measured field of existing magnets. Table 1 shows the expected D1 field based on calculations [2]. The expected field quality in the 2-in-1 D2 dipole, presented in Table 2, is obtained from scaling of the measured field of the existing MBRB dipole with 80 mm aperture. The expected field in the 2-in-1 Q4 and Q5 matching quadrupoles is shown in Tables 3,4 and is based on scaling from the measured field of the existing MQY quadrupole with 70 mm aperture. In fact, the Q5 will be the MQY-type quadrupole, hence its field will be exactly the one of the measured MQY.

ANALYSIS AND PRELIMINARY RESULTS

As a first step, the impact of the expected magnet errors in Tables 1-4 was evaluated. In the simulations, the

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Table 1: Expected field quality in D1 at $r_0 = 50$ mm.

n	a_{nm}	a_{nu}	a_{nr}	b_{nm}	b_{nu}	b_{nr}
2	0	0.679	0.679	0	0.200	0.200
3	0	0.282	0.282	-0.900	0.727	0.727
4	0	0.444	0.444	0	0.126	0.126
5	0	0.152	0.152	0	0.365	0.365
6	0	0.176	0.176	0	0.060	0.060
7	0	0.057	0.057	0.400	0.165	0.165
8	0	0.061	0.061	0	0.027	0.027
9	0	0.020	0.020	-0.590	0.065	0.065
10	0	0.025	0.025	0	0.008	0.008
11	0	0.007	0.007	0.470	0.019	0.019
12	0	0.008	0.008	0	0.003	0.003
13	0	0.002	0.002	0	0.006	0.006
14	0	0.003	0.003	0	0.001	0.001
15	0	0.001	0.001	-0.040	0.002	0.002

Table 2: Expected field quality in D2 at $r_0 = 35$ mm.

n	a_{nm}	a_{nu}	a_{nr}	b_{nm}	b_{nu}	b_{nr}
2	0	2.545	1.591	0	6.364	0.955
3	0	1.569	0.354	0	3.290	1.519
4	0	0.846	0.966	0	0.201	0.161
5	0	0.320	0.128	0	1.089	0.577
6	0	0.408	0.306	0	0.102	0.102
7	0	0.162	0.032	0	0.162	0.162
8	0	0.077	0.077	0	0.052	0.026
9	0	0.082	0.041	0	0.410	0.205
10	0	0.131	0.065	0	0.065	0.065
11	0	0	0.104	0	1.662	0.104
12	0	0	0.165	0	0	0.165
13	0	0	0.263	0	0	0.263
14	0	0	0.418	0	0	0.418
15	0	0	0.665	0	0	0.665

Table 3: Expected field quality in Q4 at $r_0 = 30$ mm.

n	a_{nm}	a_{nu}	a_{nr}	b_{nm}	b_{nu}	b_{nr}
3	0	0.682	1.227	0	1.282	1.500
4	0	0.428	0.893	0	0.483	0.465
5	0	0.177	0.406	0	0.203	0.431
6	0	0.484	0.277	0	5.187	1.487
7	0	0.094	0.189	0	0.094	0.189
8	0	0.193	0.257	0	0.193	0.257
9	0	0.088	0.088	0	0.088	0.088
10	0	0.120	0.120	0	3.587	0.956
11	0	0.326	0.489	0	0.326	0.489
12	0	0.445	0.222	0	0.445	0.222
13	0	0.606	0.303	0	0.606	0.303
14	0	0.827	0.413	0	2.067	0.413
15	0	1.127	0.564	0	1.127	0.564

Table 4: Expected field quality in Q5 at $r_0 = 17$ mm.

n	a_{nm}	a_{nu}	a_{nr}	b_{nm}	b_{nu}	b_{nr}
3	0	0.500	0.900	0	0.940	1.100
4	0	0.230	0.480	0	0.260	0.250
5	0	0.070	0.160	0	0.080	0.170
6	0	0.140	0.080	0	1.500	0.430
7	0	0.020	0.040	0	0.020	0.040
8	0	0.030	0.040	0	0.030	0.040
9	0	0.010	0.010	0	0.010	0.010
10	0	0.010	0.010	0	0.300	0.080
11	0	0.020	0.030	0	0.020	0.030
12	0	0.020	0.010	0	0.020	0.010
13	0	0.020	0.010	0	0.020	0.010
14	0	0.020	0.010	0	0.050	0.010
15	0	0.020	0.010	0	0.020	0.010

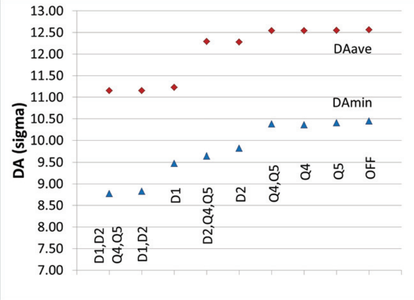

Figure 1: DA with the D1, D2, Q4, Q5 expected field errors (60 random seeds).

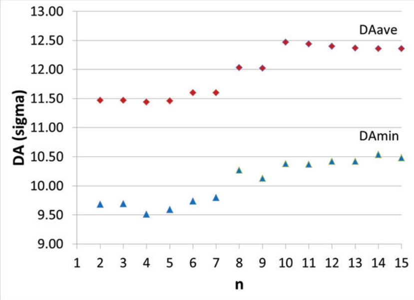

Figure 2: DA with the D1 errors, where for a given n the a_n, b_n are turned on for orders from n to 15 (30 seeds).

IT errors were set to the specifications in the table "target65" [6]. Fig. 1 shows the individual and combined effect of the new magnet field on minimum and average DA (DA$_{min}$ and DA$_{ave}$) for 60 random seeds. Clearly, the Q4 and Q5 errors have a weak effect and therefore are satisfactory. However, the D1 and D2 errors reduce the DA, hence adjustment to their specifications is required. Note that the DA$_{ave}$ is more consistent with respect to the errors while the DA$_{min}$ may be affected by the worst seed.

As a second step, the accumulated effect of the expected errors in the D1 and D2 dipoles was tested without the Q4, Q5 errors. Fig. 2,3 show the DA$_{min}$ and DA$_{ave}$ with either the D1 or D2 errors added order-by-order starting from n=15. Naturally, the DA is reduced when more terms are added, however some terms show a stronger effect. Particularly, the D1 terms $n = 5, 7, 9$ ("allowed" terms in a dipole), and the D2 low order terms create most reduction of the DA$_{ave}$. Finally, the impact of individual a_n and b_n terms up to $n = 9$ in the D1 and D2 magnets was verified when all the other terms were set to zero. The results are presented in Fig. 4,5. One can see that the DA$_{ave}$ is rather weakly affected by a single a_n or b_n term while the DA$_{min}$ is somewhat reduced by b_5, b_7 terms.

For more understanding of the individual terms, we also made a simple analytic estimate of the kicks they induce. These were calculated at the size of expected DA$_{min}$ of 10σ. The kicks were normalized to $\sqrt{\epsilon/\beta}$ and calculated for x and y planes:

$$X(b_n) = 10^{-4}(B_N L/B\rho) b_n (10\sigma_x/r_0)^{n-1}/\sqrt{\epsilon/\beta_x}, \quad (2)$$

$$Y(a_n) = 10^{-4}(B_N L/B\rho) a_n (10\sigma_y/r_0)^{n-1}/\sqrt{\epsilon/\beta_y}, \quad (3)$$

where L is the magnet length, $B\rho$ the magnetic rigidity, ϵ the emittance and β the approximate average beta function.

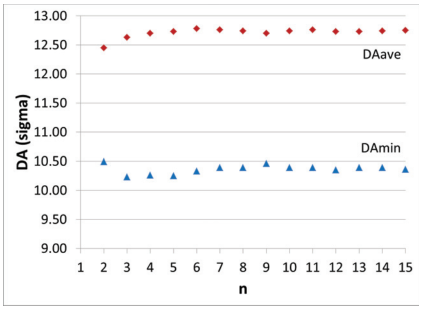

Figure 3: DA with the D2 field errors, where for a given n the a_n, b_n are turned on for orders from n to 15 (30 seeds).

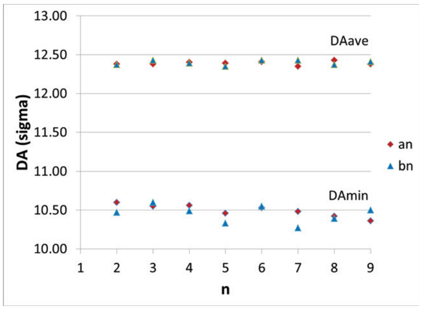

Figure 4: DA sensitivity to the individual a_n and b_n terms in the D1 (30 random seeds).

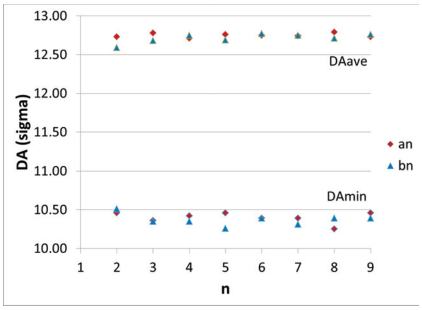

Figure 5: DA sensitivity to the individual a_n and b_n terms in the D2 (30 random seeds).

Table 5: Largest normalized kicks caused by a_n, b_n terms in D1 and D2 at 10σ in units of 10^{-2}.

	n	$Y(a_{nm})$	$Y(a_{nu})$	$Y(a_{nr})$	$X(b_{nm})$	$X(b_{nu})$	$X(b_{nr})$
D1	2	0	29	29	0	8.6	8.6
	3	0	7.0	7.0	22	18	18
	4	0	6.4	6.4	0	1.8	1.8
	5	0	1.3	1.3	0	3.0	3.0
	6	0	0.84	0.84	0	0.29	0.29
	7	0	0.16	0.16	1.1	0.46	0.46
	9	0	0.02	0.02	0.55	0.06	0.06
D2	2	0	38	24	0	96	14
	3	0	9.6	2.2	0	20	9.3
	4	0	2.1	2.4	0	0.50	0.40
	5	0	0.33	0.13	0	1.1	0.59

Table 6: Adjusted field coefficients in D1 and D2 dipoles.

	n	a_{nu}	a_{nr}	b_{nm}	b_{nu}	b_{nr}
D1 $r_0 = 50$ mm	5	0.076	0.076		0.183	0.183
	6	0.088	0.088			
	7			0.200	0.083	0.083
	9			-0.295		
D2 $r_0 = 35$ mm	2	1.273	0.796		3.182	0.478
	3	0.785	0.177		1.645	0.760
	4	0.423	0.483			
	5				0.545	0.289

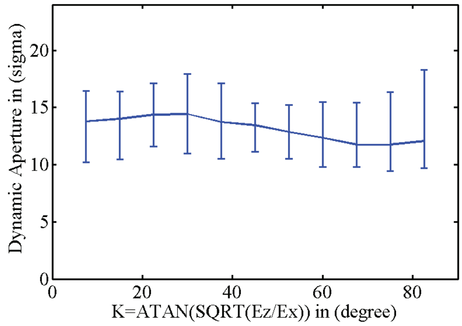

Figure 6: DA for the adjusted field quality in the D1, D2, Q4, Q5 magnets, where the line is DA$_{ave}$ and the bars show the DA spread for 60 random seeds.

Table 5 shows the largest kicks in the D1 and D2 dipoles in units of 10^{-2}. Only the value for the dominant magnet on the left or right side of the IP is shown. Note that the IT correctors compensate the D1 $n{=}3, 4$ and b_6 terms in this lattice layout. The large $n = 2$ kicks are compensated with the tune and coupling correction systems, and the chromatic tune shift from b_3 in D2 is corrected with the ring chromaticity correction system.

The uncorrected kicks to be noted in the D1 are due to $a_5, b_5, a_6, b_7, b_{9m}$ which is in agreement with the earlier DA results. For the D2 magnet, one can note the $n{=}2, 3$ terms because they are particularly large and may not be efficiently corrected with the global systems, and the terms a_4, b_5. Based on these findings, we set these terms preliminary to 50% relative to the values in Tables 1,2 as shown in Table 6. The resultant dynamic aperture is shown in Fig. 6 where the DA$_{min}$ $= 9.43\sigma$. It should be noted that this value is influenced by a single bad error seed. Without this seed the DA$_{min}$ would be 9.81σ. Therefore, the potential DA reduction due to the D1, D2, Q4, Q5 field errors is in the range of 0.5-1σ. These results are preliminary. More detailed tracking studies are needed for final specification of the field quality. These should include the feed-down effects in the D1, D2 and the planned a_5, b_5, a_6 IT correctors. The latter should relax the D1 a_5, b_5, a_6 terms in Table 6.

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