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INITIAL ESTIMATES OF DYNAMIC APERTURE AND FIELD QUALITY SPECIFICATIONS[*†]

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Abstract

In this document the results of the studies performed to determine the initial estimate of the field quality of the inner triplet quadrupoles of the HL-LHC are presented and discussed. These estimates are based on the computation of the dynamic aperture and its dependence on the field quality of the inner triplet quadrupoles. The outcome in terms of error table will be given as well. The preliminary results concerning the impact on the dynamic aperture of the expected field quality of the separation dipoles and the matching section quadrupoles will be discussed, too.

FP7 High Luminosity Large Hadron Collider Design Study
HiLumi LHC Milestone Report
23 January 2014

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[†] The HiLumi LHC Design Study is included in the High Luminosity LHC Project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Milestone Report

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FP7 High Luminosity Large Hadron Collider Design Study

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MILESTONE REPORT

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In this document the results of the studies performed to determine the initial estimate of the field quality of the inner triplet quadrupoles of the HL-LHC are presented and discussed. These estimates are based on the computation of the dynamic aperture and its dependence on the field quality of the inner triplet quadrupoles. The outcome in terms of error table will be given as well. The preliminary results concerning the impact on the dynamic aperture of the expected field quality of the separation dipoles and the matching section quadrupoles will be discussed, too.

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Executive summary

In this report the target field quality for the inner triplets is given. This initial specification is based on the most recent estimate of the expected field quality provided by the magnet designers. The expected field quality has been probed by means of massive numerical simulations, which are aimed at computing the dynamic aperture and its dependence on the triplet quadrupoles field imperfections. The initial estimate of the required field quality will be further analysed against measured data, whenever available, in view of possible refinement of the target errors.

A preliminary check of the impact of the field quality of the other insertion magnets, both separation dipoles and quadrupoles, from D1 to Q5 has been made and a quantitative specification of the field quality will follow, always based on the expected field quality estimates.

1. INTRODUCTION

The figure-of-merit that has been used since the initial steps of the design of the nominal LHC [1] to determine the required field quality of the various magnet classes is the so-called dynamic aperture. This represents the volume in phase space of the region where bounded motion occurs. Its computation is based on massive numerical simulations that scan over the phase space parameters, such as the directions in the x-y physical space, and the density of initial conditions for each direction used. The total number of turn is fixed to 10^5, and the initial momentum co-ordinate is set to 2/3 of the bucket height. In order to take into account the various sources of uncertainties in the magnetic field errors, sixty realisations of the random components, corresponding to sixty realisations of the LHC lattice, are considered in the numerical simulations. All these parameters have been specified during the design of the nominal LHC. Due to the increased computing power since then, it has been possible to increase the number of directions considered in the studies, thus making the Dynamic Aperture (DA) estimate more accurate.

For reference, the multipole expansion used to describe the magnetic field reads as [1]

$$B_y + iB_x = B_{ref} \sum_{n=1}^{\infty} \left(b_n + ia_n\right) \left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

where B_x, B_y, B_{ref} are the transverse magnetic field components and the reference field, respectively. The coefficients a_n, b_n are the so-called skew and normal field components, which are expressed in units of 10^{-4}, and R_{ref} is a reference radius at which the multipoles are expressed. It is worth recalling that in the framework of the LHC studies the magnetic errors are split into three components, namely mean (S), uncertainty (U), and random (R), such that a given multipole is obtained by

$$b_n = b_{n_S} + \frac{\xi_U}{1.5} b_{n_U} + \xi_R b_{n_R}$$

where ξ_U, ξ_R are Gaussian distributed random variables cut at 1.5 σ and 3 σ, respectively. The ξ_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, ξ_R changes also from magnet to magnet.

The studies presented in this report focus on the assessment of the field quality acceptable from beam dynamics considerations for the triplet quadrupoles at top energy. It is well-known that, due to the extremely high values of the beta-functions for the squeezed optics, the triplets have an impact on the beam dynamics that dominates to a large extent the effect of the other magnet classes. In our simulations the machine as-built is considered, i.e., the best knowledge of the measured magnetic errors is assigned to the magnets as-installed, while for the magnets that will be replaced according to the upgrade plans the expected error table, with statistical assignment of errors, is used. This is the baseline configuration of the LHC ring to which magnetic field errors of other classes of magnets can be selectively added.

In this study [2], the optimization has been performed for the LHC upgrade layout version SLHCV3.01, where the IT quadrupole gradient is 123 T/m and $\beta^*_{x,y}$=15 cm at IP1 and IP5. The acceptable minimum DA was set to 10.5σ, where σ is the rms beam size based on the experience achieved with the LHC [3]. The DA calculation was done using long-term tracking in SixTrack [4]. Note that the number of turns and random seeds affects the accuracy of the DA calculation which is at least 0.1σ in this case. No beam-beam effects are included in this study.

It is clear that the target value of the field quality based on DA computations depends on the value of the expected field quality (effectively the optimisation of the field quality corresponds to determining the Jacobian of the DA as a function of the multipoles around the expected value of the field quality), as the problem is intrinsically non-linear. For this reason, it is of paramount importance to have a reliable estimate of the expected field quality based on detailed electromagnetic simulations. This is indeed the starting point of our studies.

In this report, the impact of the separation dipoles and matching section quadrupoles is also studied and preliminary observation reported. A detailed analysis of the impact of the feed down of magnetic multiples in the separation dipoles has also been made, showing that it is negligible.

2. TRIPLET QUADRUPOLES

Table 1 shows the latest estimate of the expected field quality in a 150 mm aperture quadrupole [5, 6]. The goal of the IT error optimization is to maximize the a_n, b_n towards the values in Table 1, while providing sufficient DA. To avoid extremely tight tolerances, we set the additional constraint that the a_n, b_n are not smaller than 50% of the expected values, as 50 % as been considered still a feasible improvement of the triplets field quality by the magnet designers [7].

Table. 1 Expected field errors in 150 mm aperture quadrupoles at R_{ref}=50 mm.

	Skew			Normal		
Multipoles	a_{nS}	a_{nU}	a_{nR}	b_{nS}	b_{nU}	b_{nR}
3	0.000	0.800	0.800	0.000	0.820	0.820
4	0.000	0.650	0.650	0.000	0.570	0.570
5	0.000	0.430	0.430	0.000	0.420	0.420
6	0.000	0.310	0.310	0.800	1.100	1.100
7	0.000	0.190	0.190	0.000	0.190	0.190
8	0.000	0.110	0.110	0.000	0.130	0.130
9	0.000	0.080	0.080	0.000	0.070	0.070
10	0.000	0.040	0.040	0.150	0.200	0.200
11	0.000	0.026	0.026	0.000	0.026	0.026
12	0.000	0.014	0.014	0.000	0.018	0.018
13	0.000	0.010	0.010	0.000	0.009	0.009
14	0.000	0.005	0.005	-0.040	0.023	0.023

It is desirable that the high order terms are not too tight since it may be more difficult to achieve their specifications. The results of previous studies [8] will help to guide the optimization. For an easy comparison with the table of expected multipoles, the a_n, b_n terms will be presented in relative units normalized to what listed in Table 1. It is worth noting that the terms b_6, b_{10}, b_{14} are relatively large since they are allowed by the intrinsic symmetry of the quadrupole coil. This also explains why the expected average values b_{6S}, b_{10S}, b_{14S} are not zero.

An initial verification of the DA obtained considering IT correctors for the compensation of a_3, b_3, a_4, b_4, b_6 terms only, showed that the goal of 10.5 s could not be achieved. Since the low order terms typically have stronger impact on the DA, it is reasonable to study additional IT correctors for a_5, b_5, a_6 terms. In fact, these correctors have been already implemented in the other LHC lattice SLHCV3.1b [9, 10].

The effect of the additional correctors has been simulated by allowing smaller a_5, b_5, a_6 values, assuming they are indeed the residual errors after the compensation procedure. To determine their acceptable settings, these terms are scanned from 0 to 50 % when all other a_n, b_n, terms are set to 50 %. The DA sensitivity in this combined scan is shown in Fig. 1. One can see that the acceptable value for the residual a_5, b_5, a_6 terms (after correction) is 20 %

providing a minimum DA of about 10.5σ. It seems reasonable to expect that the IT correctors should be able to reach such a performance, assuming the uncorrected values of a_5, b_5, a_6 are at least 50 %. The combination of IT errors where a_5, b_5, a_6 are set to 20 % and all other terms to 50 % will be further used as a reference point. Scans of the uncertainty and random terms of the a_5, b_5, a_6 show that the DA is least sensitive to the a_{5U}, a_{6U}, which can be somewhat relaxed.

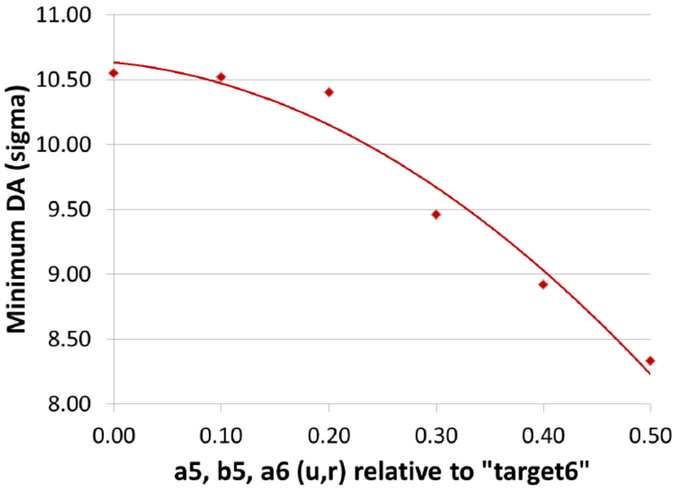

Fig. 1 Combined scan of uncertainty and random a_5, b_5, a_6 terms when all the other a_n, b_n, are set to 50 % of the errors listed in Table 1.

The previous studies determined that the IT correctors provide a reasonably good compensation for the errors up to the 6th order. Therefore, the lowest order uncorrected terms n=7, 8 have been tested first. Figure 2 (left) shows that b_7, b_8 (U, R) and a_{8R} have a visible impact on the DA. Consequently, these terms must stay at the minimal 50 % setting.

Since the expected allowed terms b_{10}, b_{14} are relatively large and the average terms b_{6S}, b_{10S}, b_{14S} are not zero, it is logical to verify their effect. The tracking confirmed that these terms, except the b_{6S}, decrease the DA at a higher than 50 % settings. Therefore, they cannot be relaxed. Examples of b_{10}, b_{14} scans are shown in Fig. 2 (right). Other tracking scans confirmed that the high order terms, especially the a_{nU}, and the corrected lowest order terms at n=3,4 have a weak impact on the DA, such that they can be set close to the values in Table 1.

The performed scans of the individual error terms and their combinations help to determine their optimal settings. However, when combined together the accumulated effect of all the terms on the DA is increased. Therefore, the final optimization of the IT error table satisfying the minimum DA requires additional adjustment to some of the terms.

The final verification has been performed by using the optimised version of the expected error table using the lattice SLHCV3.1b. As already mentioned this layout is closer to the official HL-LHCV1.0 layout, which is the baseline for the HL-LHC, and the triplet correctors' system includes the complete set of magnets.

In order to release as much as possible the constraints on the multipoles, the components a_5, b_5, a_6 are set to 100 %. In Fig. 3 the outcome of dedicated numerical simulations with 59 x-y angles are shown. The DA for the expected as well as for the optimised error table is shown.

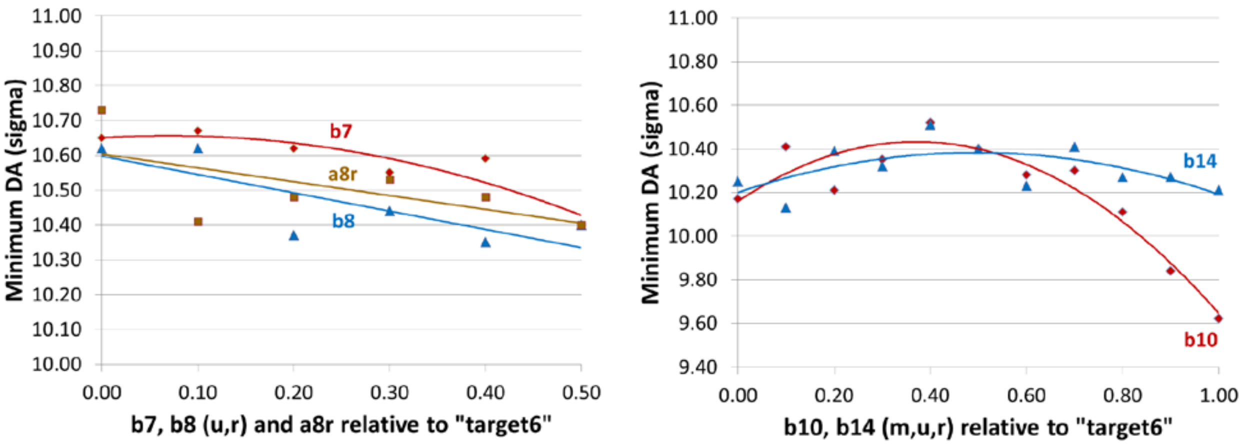

Fig. 2 Left: DA sensitivity to b_7, b_8 and a_{8R}, where b_7, b_8 include the uncertainty and random parts. Right: DA sensitivity to b_{10}, b_{14} including the mean, uncertainty and random parts.

The error bars refer to the minimum and maximum values of the DA over the sixty seeds, while the markers represent the average value. The improvement is clearly seen. At small angles both the average and minimum DA are better for the optimised error table. For larger angles the improvement is less evident, but the target value for the DA is nevertheless fulfilled. The final specification table is reported in Table 5.

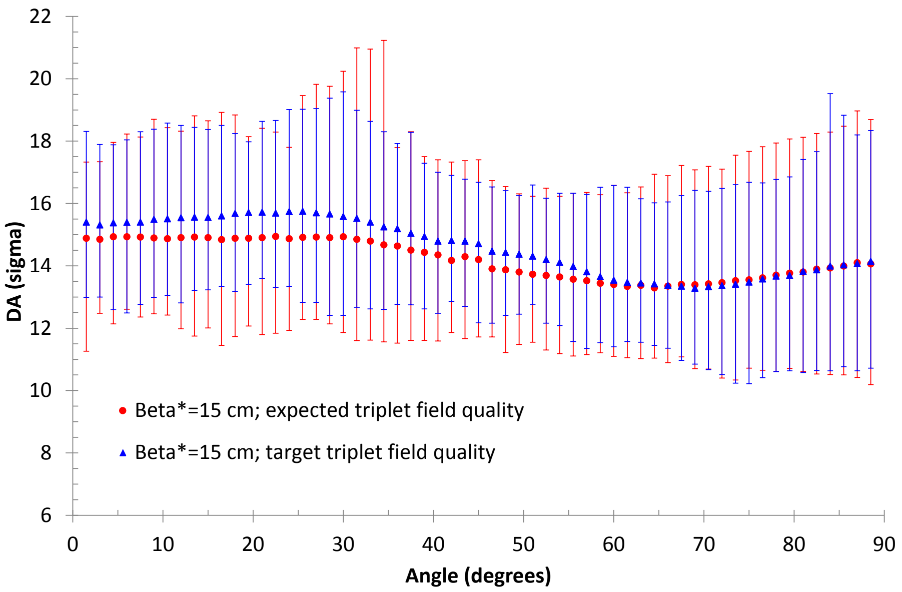

Fig. 3 DA as a function of the x-y angles for the expected (red) and the optimised (blue) error table. The lattice SLHCV3.1b has been used for the simulations. The error bars refer to the minimum and maximum DA of the sixty seeds.

3. SEPARATION DIPOLES AND MATCHING SECTION QUADRUPOLES

The next step has been the analysis of the impact of the field quality of the separation dipoles and matching section quadrupoles [11]. Table 2 shows the expected D1 field errors based on calculations [12, 13] and the expected field quality of the two-in-one D2 dipole [14], which is obtained from scaling of the measured field of the existing MBRB dipole with 80 mm aperture. The expected field in the two-in-one Q4 and Q5 matching quadrupoles is shown in Table 3 and is based on scaling from the measured field quality 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. Also in this case the lattice used has been SLHCV3.01 and it is reminded that for this lattice the IT correctors for a_5, b_5, and a6 are not implemented. It is worth mentioning that the reference radius has been agreed with magnet designer to be chosen at 1/3 of the magnet aperture.

Table 2: Expected field quality in D1 at R_{ref}=50 mm and D2 at R_{ref}=35 mm.

	D1						D2					
	Skew			Normal			Skew			Normal		
Multipole	a_{nS}	a_{nU}	a_{nR}	b_{nS}	b_{nU}	b_{nR}	a_{nS}	a_{nU}	a_{nR}	b_{nS}	b_{nU}	b_{nR}
2	0.000	0.679	0.679	0.000	0.200	0.200	0.000	2.545	1.591	0.000	6.364	0.955
3	0.000	0.282	0.282	-0.900	0.727	0.727	0.000	1.569	0.354	0.000	3.290	1.519
4	0.000	0.444	0.444	0.000	0.126	0.126	0.000	0.846	0.966	0.000	0.201	0.161
5	0.000	0.152	0.152	0.000	0.365	0.365	0.000	0.320	0.128	0.000	1.089	0.577
6	0.000	0.176	0.176	0.000	0.060	0.060	0.000	0.408	0.306	0.000	0.102	0.102
7	0.000	0.057	0.057	0.400	0.165	0.165	0.000	0.162	0.032	0.000	0.162	0.162
8	0.000	0.061	0.061	0.000	0.027	0.027	0.000	0.077	0.077	0.000	0.052	0.026
9	0.000	0.020	0.020	-0.590	0.065	0.065	0.000	0.082	0.041	0.000	0.410	0.205
10	0.000	0.025	0.025	0.000	0.008	0.008	0.000	0.131	0.065	0.000	0.065	0.065
11	0.000	0.007	0.007	0.470	0.019	0.019	0.000	0.000	0.104	0.000	1.662	0.104
12	0.000	0.008	0.008	0.000	0.003	0.003	0.000	0.000	0.165	0.000	0.000	0.165
13	0.000	0.002	0.002	0.000	0.006	0.006	0.000	0.000	0.263	0.000	0.000	0.263
14	0.000	0.003	0.003	0.000	0.001	0.001	0.000	0.000	0.418	0.000	0.000	0.418
15	0.000	0.001	0.001	-0.040	0.002	0.002	0.000	0.000	0.665	0.000	0.000	0.665

In the simulations, the IT errors were set to the specifications as given in Ref. [2]. Fig. 4 shows the individual and combined effect of the new magnet field on minimum and average DA (DA_{min} and DA_{ave}) over 60 seeds. Clearly, the Q4 and Q5 errors have a weak effect and therefore their current expected field qualities are satisfactory. However, the D1 and D2 errors reduce the DA; hence adjustment to their current expected field errors is required. Note that DA_{ave} is more consistent with respect to the multipolar errors, while DA_{min} may be affected by the worst seed and hence it would feature a worse correlation with the expected field quality.

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. 5 shows the DA_{min} and DA_{ave} with either the D1 (left) or D2 (right) 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 with n=5, 7, 9 (allowed multipoles in a dipole magnet), and the D2 low order terms create most reduction of the DA_{ave}.

Table 3: Expected field quality in Q4 at R_{ref}=30 mm and Q5 at R_{ref}=17 mm.

	Q4						Q5					
	Skew			Normal			Skew			Normal		
Multipole	a_{nS}	a_{nU}	a_{nR}	b_{nS}	b_{nU}	b_{nR}	a_{nS}	a_{nU}	a_{nR}	b_{nS}	b_{nU}	b_{nR}
3	0.000	0.682	1.227	0.000	1.282	1.500	0.000	0.500	0.900	0.000	0.940	1.100
4	0.000	0.428	0.893	0.000	0.483	0.465	0.000	0.230	0.480	0.000	0.260	0.250
5	0.000	0.177	0.406	0.000	0.203	0.431	0.000	0.070	0.160	0.000	0.080	0.170
6	0.000	0.484	0.277	0.000	5.187	1.487	0.000	0.140	0.080	0.000	1.500	0.430
7	0.000	0.094	0.189	0.000	0.094	0.189	0.000	0.020	0.040	0.000	0.020	0.040
8	0.000	0.193	0.257	0.000	0.193	0.257	0.000	0.030	0.040	0.000	0.030	0.040
9	0.000	0.088	0.088	0.000	0.088	0.088	0.000	0.010	0.010	0.000	0.010	0.010
10	0.000	0.120	0.120	0.000	3.587	0.956	0.000	0.010	0.010	0.000	0.300	0.080
11	0.000	0.326	0.489	0.000	0.326	0.489	0.000	0.020	0.030	0.000	0.020	0.030
12	0.000	0.445	0.222	0.000	0.445	0.222	0.000	0.020	0.010	0.000	0.020	0.010
13	0.000	0.606	0.303	0.000	0.606	0.303	0.000	0.020	0.010	0.000	0.020	0.010
14	0.000	0.827	0.413	0.000	2.067	0.413	0.000	0.020	0.010	0.000	0.050	0.010
15	0.000	1.127	0.564	0.000	1.127	0.564	0.000	0.020	0.010	0.000	0.020	0.010

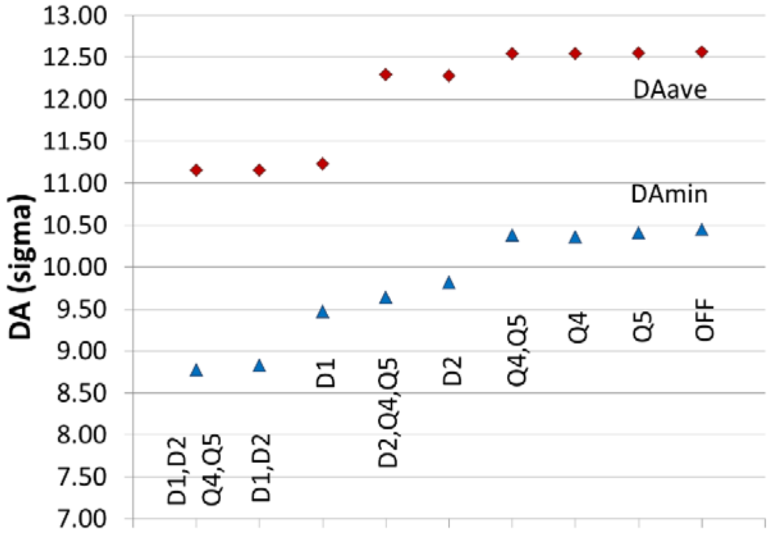

Fig. 4 DA with the IT optimised errors as from Ref. [2] as well as the expected errors for D1, D2, Q4, and Q5. Sixty seeds are considered.

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. 6 (left for

D1 and right for D2). 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.

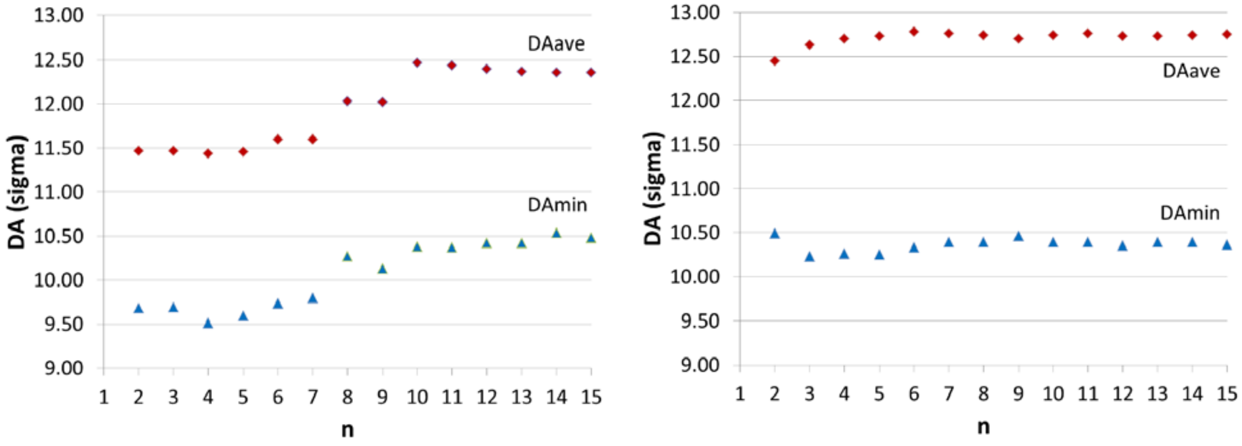

Fig. 5 DA with the D1 errors (left) or D2 errors (right), where for a given n *the* a_n *and* b_n *terms are turned on for orders from* n *to 15 (30 seeds).*

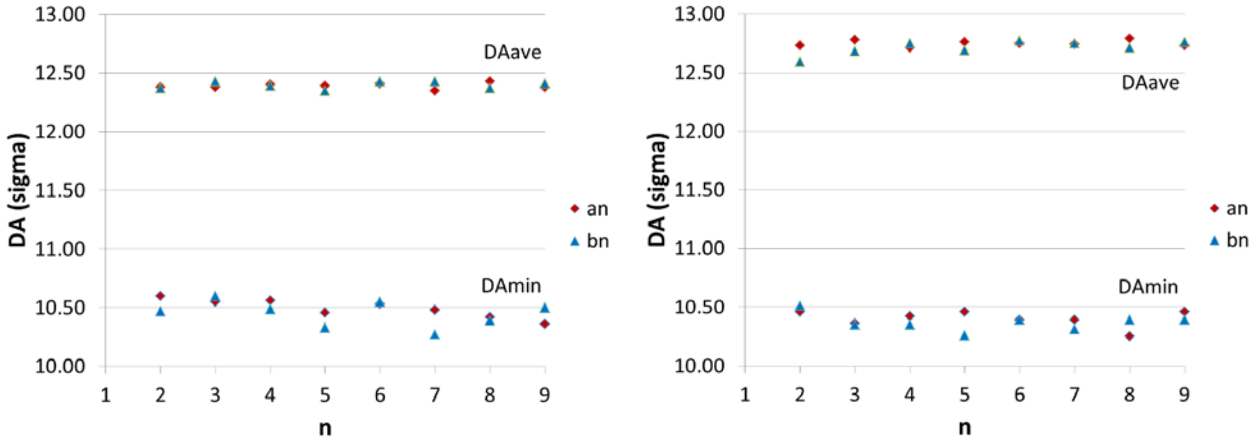

Fig. 6 DA with the D1 errors (left) or D2 errors (right), where for a given n *only the* a_n *and* b_n *terms are turned on (30 seeds).*

Based on these findings, we set these terms preliminary to 50 % relative to the values in Table 2, as shown in Table 4. The resultant dynamic aperture is shown in Fig. 7 where the DA_{min}=9.43σ. 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 expected field errors as quoted in the tables listed in this report 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 latest information on the expected field quality of the D2 [10, 11] and Q4 magnets, as well as the implementation of the planned a_5, b_5, a_6 IT correctors, which should help relaxing the bounds on the corresponding components of the D1 magnets as reported in Table 4.

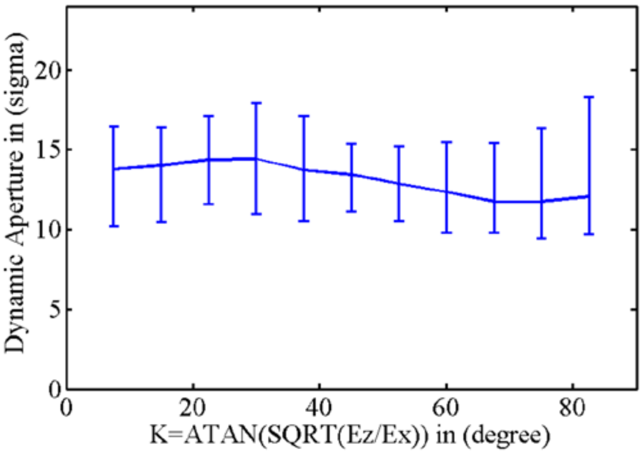

Fig. 7 DA for the adjusted field quality in the D1 and D2 separation dipoles, including also the optimised IT field quality, and the expected field quality of Q4, Q5 magnets, where the line is D_{ave} and the bars show the DA spread for 60 random seeds.

Table 4: Adjusted field quality of D1 and D2 separation dipoles.

		Skew		Normal		
	Multipoles	a_{nU}	a_{nR}	b_{nS}	b_{nU}	b_{nR}
D1 R_{ref}=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_{ref}=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

3.1. FEED DOWN EFFECTS FROM SEPARATION DIPOLES

When the beam passes through the rectangular shape separation dipoles, it experiences feed down effects from the magnetic field imperfections due to the curved orbit. This effect can be included in the numerical simulations by developing appropriate tools. The actual impact of this effect has been checked via numerical simulations using the lattice version SLHCV3.1b and including the feed down effects from the existing separation dipoles, i.e., those in IR2, 4, 8, as well as the new ones for the upgraded LHC ring. The results of the numerical simulations are shown in Fig. 8. In the upper part of Fig. 8 two scenarios are presented, namely one with only IT errors according to the specification error table (see next section), and one including also the expected field error in the new D1. These errors are found in the table called D1_errortable_v0 under [13]. Each scenario has two variants, i.e., with or without the impact of the feed down from the considered separation dipoles. It is clearly seen that the impact on the average DA is completely negligible; while on the minimum DA it is at the level of fractions of sigma, hence, this effect is not expected to change the results of the preliminary analysis of the field quality of the separation dipoles and matching section quadrupoles.

In the lower part of Fig. 8, however, the impact of the D2 expected field quality is also probed. These errors are found in the table called D2_errortable_v3 under [15]. For this specific study all the multipoles have been divided by four, assuming that a further optimisation could be performed. Also in this case the effect of the orbit feed down seems rather marginal. The observed slight increase of DA_{ave} could be the effect of compensation between the errors of the various magnet classes and the feed down effects. Furthermore, a feed down from b_3 could generate a b_2 error that would result in an increase of the value of beta-function at the IP, thus improving slightly the situation.

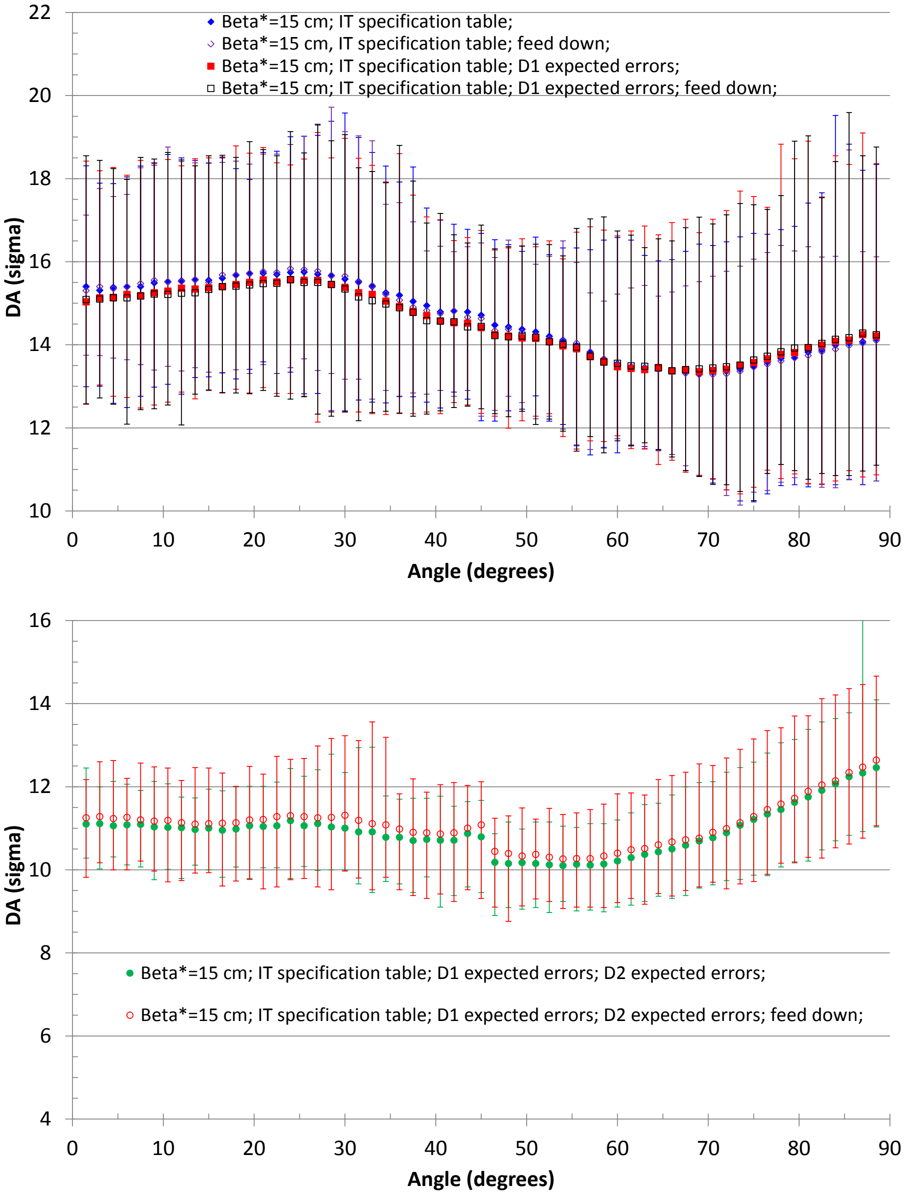

Fig. 7 Upper: DA for two scenarios of field errors (assigned only to IT or also to D1 magnets) with or without the effect of the feed down from the separation dipoles. The error bars represent the minimum and maximum DA over the sixty seeds. Lower: DA for a scenario including IT, D1, and D2 field errors, with or without the effect of the feed down from the separation dipoles. The error bars represent the minimum and maximum DA over the sixty seeds.

4. FINAL SPECIFICATION TABLES

The main result of this study is the target error table for the IT quadrupole of HL-LHC that is reported in Table 5.

Table. 5 Specification table for the IT quadrupoles at R_{ref}*=50 mm following the optimisation via numerical simulations.*

	Skew			Normal		
Multipoles	a_{nS}	a_{nU}	a_{nR}	b_{nS}	b_{nU}	b_{nR}
3	0.000	0.800	0.800	0.000	0.820	0.820
4	0.000	0.650	0.650	0.000	0.570	0.570
5	0.000	0.430	0.430	0.000	0.420	0.420
6	0.000	0.310	0.310	0.800	0.550	0.550
7	0.000	0.152	0.095	0.000	0.095	0.095
8	0.000	0.088	0.055	0.000	0.065	0.065
9	0.000	0.064	0.040	0.000	0.035	0.035
10	0.000	0.040	0.032	0.075	0.100	0.100
11	0.000	0.026	0.0208	0.000	0.0208	0.0208
12	0.000	0.014	0.014	0.000	0.0144	0.0144
13	0.000	0.010	0.010	0.000	0.0072	0.0072
14	0.000	0.005	0.005	-0.020	0.0115	0.0115

5. CONCLUSIONS AND OUTLOOK

This report gives the first estimate of the target field quality for the new IT quadrupoles of the upgraded LHC. Extensive numerical simulations have been performed to reach the current conclusions, which are based on the best estimate of the expected field quality from the magnet designers. One of the guiding criteria has been to try to avoid departing too much from the expected error table, in order to ease the construction process. It is clear that, as soon as measurement results of the field quality of prototype magnets will be available, a detailed comparison of these specifications against the measured field quality will be carried out, including also new simulation campaigns.

Preliminary results concerning the impact of the expected field quality of the separation dipoles and of the matching section quadrupoles have been also discussed here.

The next steps will focus mainly on the definition of the target field quality of the D2 separation dipole, which turned out to have a major impact on DA. The starting point will be the recent estimate of the expected field quality as given in [16], for which preliminary results of numerical simulations seem to indicate that a deep revision of the expected field quality is needed [17].

Then, the activities will move to the analysis of the new cold separation dipole D1.

The final step will be the analysis of the matching section quadrupoles, knowing that they are not expected to have a major impact on DA.

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ANNEX: GLOSSARY

Acronym	**Definition**
DA	Dynamic aperture
FQ	Field quality
IP	Interaction point
IR	Interaction region
IT	Inner triplet
D1	First separation dipole just downstream of the triplet quadrupoles
D2	Second separation dipole downstream of D1