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DYNAMIC APERTURE STUDIES FOR THE LHC HIGH LUMINOSITY LATTICE*

R. de Maria, M. Giovannozzi, E. McIntosh, CERN, Geneva, Switzerland
Y. Cai, Y. Nosochkov†, M-H. Wang, SLAC, Menlo Park, CA 94025, USA

Abstract

Since quite some time, dynamic aperture studies have been undertaken with the aim of specifying the required field quality of the new magnets that will be installed in the LHC ring in the framework of the high-luminosity upgrade. In this paper the latest results concerning the specification work will be presented, taking into account both injection and collision energies and the field quality contribution from all the magnets in the newly designed interaction regions.

INTRODUCTION

The low-β optics of the high luminosity LHC [1] demands very stringent requirements on the field quality (FQ) of the new large aperture interaction region (IR) magnets: the inner triplet (IT) quadrupoles, the D1 and D2 separation dipoles, and the Q4 and Q5 matching quadrupoles. Specifications of the FQ of these magnets have been studied based on dynamic aperture (DA) calculations with the goal of reaching an acceptable minimum DA ($\simeq 10\sigma$) while being realistically close to the expected magnet FQ. The latter is based on magnet design or scaling from existing magnets FQ. In this paper, the impact of the latest FQ estimate of the IT and Q4 quadrupoles, and the D2 dipoles on DA at collision and injection energies is analyzed, and the necessary adjustments to this FQ are proposed.

The DA study was done for the latest HLLHCV1.0 lattice [2]. Nominally, the so-called `round` beam optics at collision energy was used, where $\beta^*_{x,y}$ = 15 cm at the interaction points IP1 and IP5. In this study, we extend the simulations to other lattice options with different values of β^* which will be described in more detail later. The DA of these lattices was also studied for an extended range of machine linear chromaticity ξ from +2 (nominal) to +18.

The DA was obtained using SixTrack [3,4] with the following set-up: 10^5 turns, 11 x-y phase space angles, 30 particle pairs per $2\,\sigma$ amplitude step, 60 random error seeds, normalized emittance of 3.75 μm, $\Delta p/p = 2.7\cdot10^{-4}$ and $7.5\cdot10^{-4}$ at 7 TeV (collision) and 450 GeV (injection) beam energy, respectively. The machine errors included the arc field errors based on measured FQ of the existing magnets, and the IR magnet field errors based on the latest FQ specifications. The simulations included the correction of tune, chromaticity, coupling and orbit, the use of b_3, b_4, b_5 correctors in the arc dipoles, as well as the IT non-linear field correctors up to the 6th order [5]. Beam-beam effects were not included in this study.

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† yuri@slac.stanford.edu

LATEST FIELD QUALITY

The FQ of LHC magnets is defined by [6]

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

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. [5]).

The FQ tables for the new IR magnets can be found at the official LHC repository [7]. The recent updates include the new FQ estimates for the IT and Q4 quadrupoles, and for the D2 dipoles.

D2 and Q4 Magnets

The new estimate of the D2 FQ is referred to as `D2_errortable_v5` and includes an update to several b_n coefficients at both the collision and injection energies [8]. The impact of the D2 FQ at collision energy was verified previously [9] and found acceptable since it improved the minimum DA to DA$_{\min} = 9.85\,\sigma$. It has been designated the new D2 FQ specification. The updated D2 FQ coefficients at injection energy are shown in Table 1. The new non-zero b_2 term affects the linear optics. In machine operation the IR focusing errors are expected to be compensated. However, due to lack of such correction in the simulations, this term was set to zero to avoid its impact on the DA. With this assumption, the effect of the updated D2 FQ on DA at injection energy was found negligible and, hence, this FQ is acceptable as a new D2 specification. In this case, the DA$_{\min} = 9.92\,\sigma$.

Table 1: Updated Coefficients of the D2 FQ at Injection Energy (r_0 = 35 mm). Old Values are Shown for Reference

	b_{2m}	b_{3m}	b_{4m}	b_{6m}	b_{7m}	b_{8m}	b_{9m}
Old	0	3.8	-8.0	0	0.1	0	0.02
New	5.0	-19.0	2.0	2.0	1.3	1.0	0.52

The new estimate of Q4 FQ is referred to as `Q4_errortable_v2` and it affects all the field coefficients. In this update, the high order terms (n>9) are reduced at the expense of somewhat larger low order coefficients. Also, new non-zero systematic terms are introduced: b_{6m}, b_{14m} at collision energy and b_{6m}, b_{10m}, b_{14m} at injection. On the other hand, the corresponding uncertainty and random terms b_{nu}, b_{nr} of order n=6,10,14 are cancelled. The SixTrack calculations showed negligible impact of this Q4 FQ

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on the DA at both collision and injection energies, hence it is considered acceptable as a new Q4 specification.

IT Quadrupoles

FQ of the IT quadrupoles had been extensively optimized in the past (see, e.g., Refs. [9, 10]). The recent update combines the previously made optimization and the new estimates of systematic terms b_{6m}, b_{10m}, b_{14m} as shown in Table 2. This FQ is referred to as `IT_errortable_v66_4` in [7].

Table 2: Updated Coefficients of the IT FQ (r_0 = 50 mm). The Old Values are Shown in Brackets

Collision	b_{6m}	b_{10m}	b_{14m}
	0.4 (0.8)	-0.39 (0.075)	-0.67 (-0.02)
Injection	b_{6m}	b_{10m}	b_{14m}
	-15.8 (-16)	3.63 (4.15)	-0.6 (-0.04)

One can see the significantly increased b_{10m} and b_{14m} at collision energy. The calculations showed that both the minimum and average DA at collision were considerably reduced from $\mathrm{DA_{min}} = 9.85\,\sigma$ to $8.34\,\sigma$ and from $\mathrm{DA_{ave}} = 12.47\,\sigma$ to $9.65\,\sigma$ as compared to the previous IT FQ (`IT_errortable_v3_spec`). Figure 1 shows a consistent reduction of the average DA due to both terms, however the relative impact of the b_{14m} is stronger. Similar sensitivity is obtained for the minimum DA, although its dependence is not as smooth due to DA fluctuations of the worst seeds. In order to recover the DA, these terms have to be reduced, however they should remain within reach relative to the expected magnet FQ. As a compromise, the b_{10m} and b_{14m} were scaled by 0.4 and 0.25 factors, respectively, relative to the `IT_errortable_v66_4`, i.e. $b_{10m} = -0.156$ and $b_{14m} = -0.1675$. The complete IT FQ with these adjustments is shown in Table 3. The resulting DA at 7 TeV is presented in Fig. 2, where the circles indicate DA for all 60 random seeds of machine errors. In this case $\mathrm{DA_{min}} = 9.10\,\sigma$ and $\mathrm{DA_{ave}} = 11.16\,\sigma$. One can notice in Fig. 2 that only a few points correspond to a DA lower than $10\,\sigma$. Further analysis showed two bad seeds consistently producing the lowest DA. Without these two seeds the minimum DA at 7 TeV would be $9.52\,\sigma$.

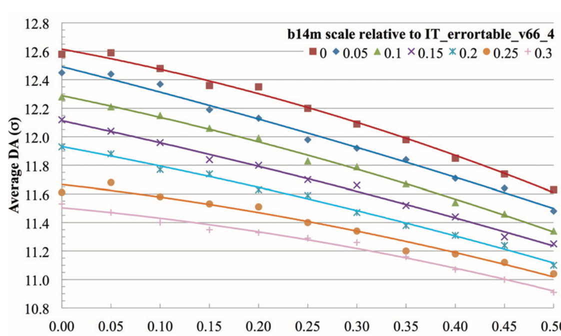

Figure 1: Average DA versus b_{10m} and b_{14m} of the IT FQ (normalized to `IT_errortable_v66_4` values) at 7 TeV.

Table 3: The IT FQ at Collision Energy with Adjusted b_{10m} b_{14m} Coefficients (r_0 = 50 mm)

n	a_{nm}	a_{nu}	a_{nr}	b_{nm}	b_{nu}	b_{nr}
3	0	0.800	0.800	0	0.820	0.820
4	0	0.650	0.650	0	0.570	0.570
5	0	0.430	0.430	0	0.420	0.420
6	0	0.310	0.310	0.400	0.550	0.550
7	0	0.152	0.095	0	0.095	0.095
8	0	0.088	0.055	0	0.065	0.065
9	0	0.064	0.040	0	0.035	0.035
10	0	0.040	0.032	-0.156	0.100	0.100
11	0	0.026	0.0208	0	0.0208	0.0208
12	0	0.014	0.014	0	0.0144	0.0144
13	0	0.010	0.010	0	0.0072	0.0072
14	0	0.005	0.005	-0.1675	0.0115	0.0115

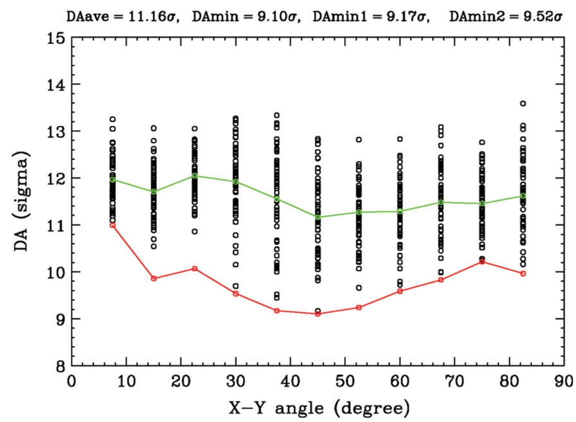

Figure 2: Dynamic aperture at collision energy with adjusted IT FQ ($\mathrm{DA_{ave}}$, green line, $\mathrm{DA_{min}}$, red line).

The impact of the updated IT FQ at injection energy was verified as well. In this case, the main concern was the b_{14m} term which is 15 times larger than in the previous IT FQ. However, the resulting DA showed a negligible effect. This is due to the fact that the IT beta functions in the injection lattice, where $\beta^* = 6$ m, are about 40 times lower as compared to the collision optics resulting in much weaker effects of the IT field errors. The minimum and average DA in this case are $9.94\,\sigma$ and $10.40\,\sigma$, respectively. Therefore, the updated IT FQ estimate at injection energy is acceptable.

DA VS β^* AND CHROMATICITY

The above study at collision energy was performed for the nominal `round` beam optics, where $\beta^*_{x,y}$ = 15 cm at IP1 and IP5. However, it is important to assess the impact of the field quality during the squeeze sequence, for several final optical configurations, and as a function of the linear chromaticity requested for stability reasons.

The ring lattices under consideration include the options where β^*_x and β^*_y are different, but their product remains the same for the same luminosity, and the so-called "super" beta options where $\beta^*_{x,y}$ are reduced by a factor of 1.5 for a higher luminosity. In this study, we compared DA for six lattices with the following β^*_x/β^*_y at IP1 and IP5: `round`

(15/15 cm), `sround` (10/10 cm), `flat` (7.5/30 cm, 30/7.5 cm), `flathv` (30/7.5 cm, 7.5/30 cm), `sflat` (5/20 cm, 20/5 cm), and `sflathv` (20/5 cm, 5/20 cm). A parallel separation of 0.75 mm is used in the simulations. Moreover, the crossing angle for the `round` and `sround` configurations is set to provide 12.5 σ of beam-beam separation (when the parallel separation is not present) at the parasitic encounters, while for the `flat`, `flathv`, `sflat`, `sflathv` it provides 15.5 σ of beam-beam separation (when the parallel separation is not present) at the parasitic encounters. The other optics for the squeeze sequence towards the `round` final state feature a constant crossing angle providing a beam-beam separation of 12.5 $\sigma\sqrt{\beta^*/15}$.

Another parameter of interest is the machine linear chromaticity ξ which may be varied in a wide range in operations. Consequently, the DA of the above lattices was also studied as a function of chromaticity in the range from +2 (nominal) to +18. The updated FQ of the IR magnets (with IT FQ adjustment) were used in these calculations.

In Fig. 3 the evolution of the DA vs β^* and for several final optical configurations is shown, with the FQ used for the triplets being `IT_errortable_v3_spec`. A similar study had been carried out in the past for an earlier HL-LHC layout [11] and the results are comparable, taking into account the layout modifications and the change in the FQ estimates used for the numerical simulations. The DA improves considerably even for a minor increase of β^*. Moreover, it is clearly seen that DA for different configurations, even non-round, have very similar DA as long as they are labelled according to $\beta^*_{\rm ave} = \sqrt{\beta^*_x\,\beta^*_y}$. Finally, the exchange of crossing plane, e.g., in `flathv` and `sflathv`, between IP1 and 5 does not change DA.

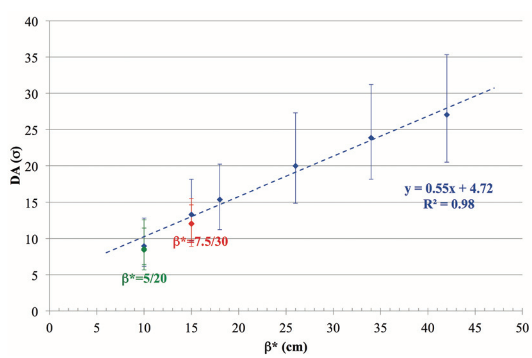

Figure 3: DA vs β^* for several final optical configurations and during the nominal squeeze sequence for round optics. The FQ used for the triplets is `IT_errortable_v3_spec`. The markers refer to DA$_{\rm ave}$, while the error bars refer to the minimum and maximum DA over the seeds.

The resulting DA for these lattices as a function of linear chromaticity are presented in Fig. 4, with adjusted IT FQ. The Fig. 4 (top) shows the three nominal luminosity lattices, while the Fig. 4 (bottom) presents the higher luminosity lattices. Comparison of the two figures shows that the higher luminosity lattices result, on average, in 3 σ smaller DA. This is due to the $\simeq$ 50% higher beta functions in the IR magnets leading to much stronger error effects. Comparison between different β^* options shows that the `flathv` and `sflathv` lattices consistently produce a larger DA$_{\rm min}$ within their groups. Although the `round` optics has slightly better DA$_{\rm ave}$ at the nominal chromaticity, but it is more sensitive at a higher ξ than the other lattices. Within the high luminosity options, the `sflat` and `sflathv` lattices have consistently better DA$_{\rm ave}$ as compared to the `sround` lattice. These points will be analysed in more detail in further studies.

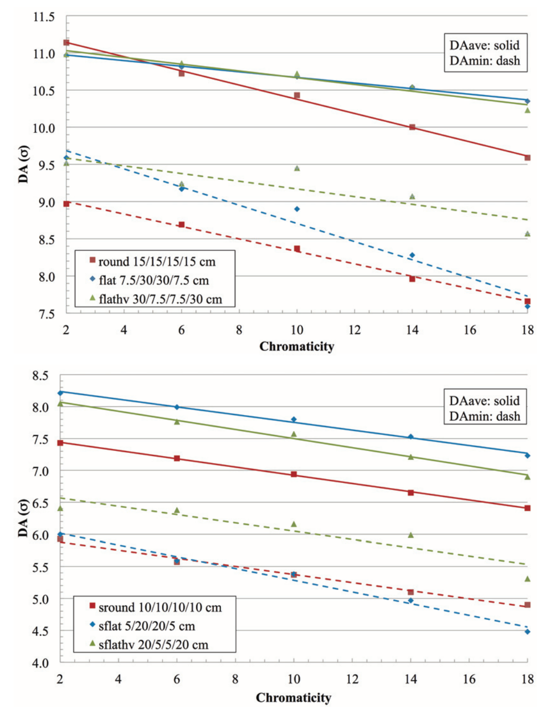

Figure 4: Top: Minimum and average DA vs linear chromaticity for `round`, `flat` and `flathv` lattices. Bottom: Minimum and average DA versus linear chromaticity for `sround`, `sflat` and `sflathv` lattices. The four numbers in the legend refer to the β^* values in IP1 and 5, respectively.

CONCLUSIONS

In this paper, the impact of the latest FQ estimates for the insertion region magnets for the HL-LHC projects has been presented. These studies considered also a revision of the systematic b_6, b_{10}, b_{14} components in IT. Injection and collision energy cases have been considered and the situation is complying with the criteria set for the DA at injection, while at top energy for the nominal round optics DA is lower that 10 σ. The ultimate check will be performed including also the beam-beam effects.

In addition, the DA as a function of β^* for several optical configurations as well as during the squeeze sequence has been computed, showing that DA improves dramatically when β^* is increased even by a small amount. Finally, the impact of linear chromaticity has been assessed, too. In general, DA features a linear dependence on ξ, with a maximum DA loss of about 2 σ.

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