SPECIFICATIONS OF THE FIELD QUALITY AT INJECTION ENERGY OF THE NEW MAGNETS FOR THE HL-LHC UPGRADE PROJECT *

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Abstract

The HL-LHC project relies on new magnet designs and technologies to achieve very small beta* values. In particular, Nb3Sn magnets show large allowed multipole imperfections at low current. These field imperfections may have a non-negligible impact on the dynamic aperture and beam life time in the HL-LHC, also because of the smaller-than-nominal beta* values foreseen IR1 and IR5 at injection energy, which aims at decreasing the dynamic range of the squeeze and therefore contributing to optimize the turn around time. The paper describes an analysis of the machine performance based on analytical estimates and tracking simulations with the goal of providing field quality specifications for the new magnets.

INTRODUCTION

The HL-LHC project [1] relies on new magnets to be installed in the LHC tunnel to achieve very small values of β^* at collision energy. In particular, Nb_3Sn technology is proposed as baseline for the triplet quadrupoles (IT). This choice might imply larger allowed multipole components, b_6 and b_{10}, with respect to the NbTi technology, due to large filament size and the resulting magnetization effects at injection currents. In addition, new optics configurations at injection have been developed [2] to take advantage of the larger aperture in view of speeding up the squeeze process. The HL-LHC relies also on other new magnets like D1-2, Q4 in IR1,5, and Q5 in IR1,5,6, labeled as matching section (MS) magnets, which are less critical in this context but whose field quality has not been specified yet and needs to be included to obtain a complete picture. The resulting field quality specifications aim at preserving the excellent dynamic aperture and lifetime of the LHC at injection [3, 4].

METHODS

The methodology used for the assessment of the field quality of a magnet type follows the same lines used for the nominal LHC [5]. 60 different models (called seeds) of the LHC Beam 1 sequence are generated by setting the magnetic imperfections of the magnets from a statistical description of each magnet class defined by three values for each multipole (the uncertainty U, random part R and the mean M) or by a set of predefined tables derived from magnetic measurements of the existing magnets [6]. For the former case, a value per seed, multipole component, magnet is generated using $b_n = b_{nS} + \frac{\xi_U}{1.5} b_{nU} + \xi_R b_{nR}$, where ξ_U, ξ_R are Gaussian distributed random variables cut at $1.5\,\sigma$ and $3\,\sigma$ and thrown for each magnet type and single magnet respectively. When specified beam-beam lenses are generated to model the head-on and long range collision in IR1,5,2,8. The thin model of the lattice is generated for long term tracking studies after that the linear and non linear correctors are setup according to correction strategies (see [7, 8] for a detailed description) that compensate local multipole errors in the triplet and in the arcs and correct tune, coupling and chromaticity.

In this particular study all the a_1, b_1 and quadrupole b_2 are set to zero to avoid the correction of orbit and β-beating (a small fraction of β-beating is inserted due to the small b_2 errors of the dipoles). A set of particle trajectories, defined by the amplitude in the $x - y$ plane expressed in $\sigma_{x,y} = \sqrt{\epsilon/\gamma\beta_{x,y}}$ in a polar grid ($\epsilon = 3.75\ \mu$rad) and a momentum offset $\delta_p = 7.5 \cdot 10^{-4}$, are tracked in the thin model using SixTrack for 10^5 and sometimes 10^6 turns and the trajectories post-processed. For this analysis the amplitude of first unstable particle for each ratio of the initial amplitudes is reported as dynamic aperture (DA).

Differently for the nominal LHC, the HL-LHC baseline foresee triplet correctors also for a_5, b_5, a_6. As for the other error sources, the correction strategy cancel some driving terms and minimize the rest. For b_6, the most relevant error source for this study, the choice was to cancel (6,0) and (0,6) when minimizing automatically (4,2) and (2,4). The effects of the feed-down due to the crossing angle is not taken into account directly, but automatically minimized because the variation of the variations of the normalized orbit at the location of the imperfections and the corrections are very small.

This correction strategy has been tested by computing the tune footprint by both numerical tracking and analytical formulas:

$$\Delta Q_x = \frac{1}{4\pi} b_2 l \beta_x \qquad \Delta Q_y = -\frac{1}{4\pi} b_2 l \beta_y$$
$$\Delta Q_x = \frac{3}{8\pi} b_4 l \beta_x \left(\beta_x J_x - 2\beta_y J_y\right)$$
$$\Delta Q_y = \frac{3}{8\pi} b_4 l \beta_y \left(-2\beta_x J_x + \beta_y J_y\right)$$
$$\Delta Q_x = \frac{5}{8\pi} b_6 l \beta_x \left(\beta_x^2 J_x^2 - 6\beta_x \beta_y J_x J_y + 3\beta_y^2 J_y^2\right)$$
$$\Delta Q_y = -\frac{5}{8\pi} b_6 l \beta_y \left(3\beta_x^2 J_x^2 - 6\beta_x \beta_y J_x J_y + \beta_y^2 J_y^2\right),$$

derived from first order perturbation theory, where b_n and a_n are defined for simplicity as $b_{n+1} = \frac{eB_{n+1}}{pR_r^n}$ and $a_{n+1} = \frac{eA_{n+1}}{pR_r^n}$ with $B_y + iB_x = \sum(B_{n+1} + iA_{n+1})((x+iy)/R_r)^n)$. The feed-down effects are included in the calculation using:

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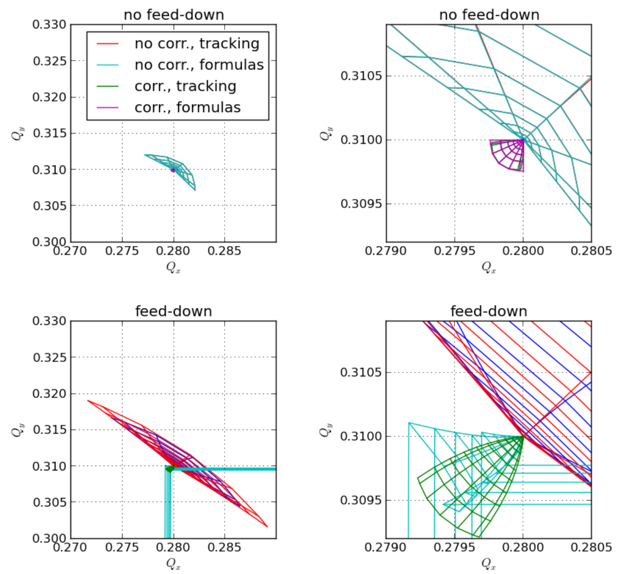

Figure 1: Tune footprint up to 12σ from $b_6 = 100$ units in the triplets and no crossing angle with and without compensation with nearby correction. The right figures are a zoom of the left ones. Footprints are derived from tracking data and analytical formulas from first order perturbation theory showing good agreement.

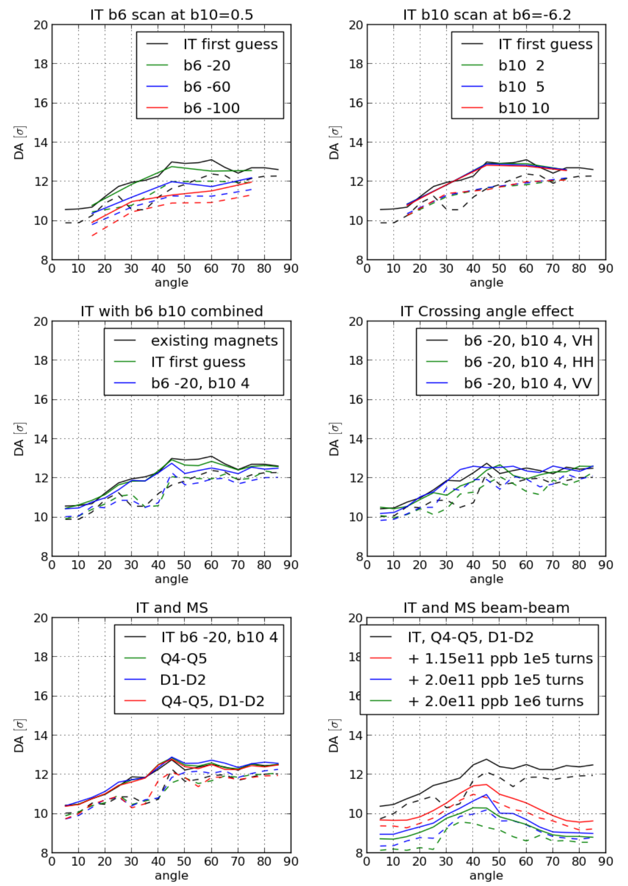

Figure 2: Dynamic aperture results of the field quality specification process. Solid and dashed lines are the average and minimum DA over the seeds, respectively. From left to right and top to bottom: separate scans of the b_6 and b_{10} components, combined effects for different crossing angle planes, inclusion of the matching section magnets and beam-beam.

$$\tilde{b}_n + i\tilde{a}_n = \sum_{k=n}^{N} \binom{k}{n} (b_k + i a_k)(x+iy)^{k-n}$$

and in particular $\tilde{b}_4 = b_4 + 15 b_6 x_0^2 - 15 b_6 y_0^2$, where (x_0, y_0) are the transverse orbit displacement.

Figure 1 shows an example for a strong b_6 component and the lesson derived to guide the hardware specifications. In the case with crossing angle the tune footprint is sensibly wider and the correction, while being effective to first order, shows second order effects that makes the motion non-regular showing fundamental limitations to extent of a correction strategy. These results support the fact that even local correctors cannot fully compensate nonlinear errors and efforts should be made to reduce the large sources of magnetic imperfections as much as reasonably possible.

SPECIFICATION STRATEGY

The overall strategy used for the field quality specifications of the new HL-LHC magnets at injection is:

- start from a reasonable guess of the field quality specification for the new triplets from existing designs;
- scan the mean and random part of b_6 and b_{10} with a fixed ratio individually to identify the values for which the DA starts to decrease in presence of the imperfections of existing LHC magnets;
- set a value for the two components and check the overall DA for the choice on b_6 and b_{10} combined;
- add the imperfections of D1-D2 and Q4-Q5 from a starting guess and check the effect on DA,
- combine all the imperfections without and with beam beam for 10^5 and 10^6 turns.

In the following the b_n and a_n are defined using the usual LHC conventions, e.g. $b_n = 10^4 B_n / B_N$, where B_N is the nominal field reference. The results of this strategy are summarized in Figure 2. The effect of different crossing angle planes has been evaluated and it is negligible. The proposed field quality specifications are in the shown Table 1-4. Overall the degradation with respect to the present LHC is less than 1σ and therefore acceptable.

CONCLUSION

The fields quality at injection current of the new magnets for the HL-LHC have been specified. The specification process has been described and justified through numerical simulations and analytical estimates, proving the effectiveness and the range of validity the correction strategy.

Table 1: Proposed Specification for the Field Quality of the 150 mm Nb_3Sn Triplets at Injection, Originating from the Phase I Triplet Proposed Field Quality Rescaled to Have the Same Numerical Value at $\mathbf{R_r} = \mathbf{50\ mm}$ Instead 40 mm. In red enlarged specifications for the allowed multipoles.

n	b_m	b_u	b_r	b_m	b_u	b_r
1	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.460	0.890	0.000	0.890	0.890
4	0.000	0.640	0.640	0.000	0.640	0.640
5	0.000	0.460	0.460	0.000	0.460	0.460
6	-20.000	1.770	4.000	0.000	1.270	0.330
7	0.000	0.210	0.210	0.000	0.210	0.210
8	0.000	0.160	0.160	0.000	0.160	0.160
9	0.000	0.080	0.080	0.000	0.080	0.080
10	4.000	0.200	0.800	0.000	0.140	0.060
11	0.000	0.030	0.030	0.000	0.030	0.030
12	0.000	0.020	0.020	0.000	0.020	0.020
13	0.000	0.020	0.010	0.000	0.010	0.010
14	-0.270	0.040	0.010	0.000	0.030	0.010
15	0.000	0.000	0.000	0.000	0.000	0.000

Table 2: Proposed Specification for the Field Quality of 150 mm D1 at Injection Based on the RHIC DX Magnet Rescaled to Have the Same Numerical Value at $\mathbf{R_r} = \mathbf{50\ mm}$ Instead 40 mm

n	b_m	b_u	b_r	a_m	a_u	a_r
1	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.500	0.600	0.000	2.000	2.000
3	-5.000	2.500	1.100	-1.000	2.000	0.300
4	0.000	0.200	0.100	0.000	0.300	0.400
5	0.000	1.000	0.100	0.000	0.100	0.050
6	0.000	0.050	0.020	0.000	0.100	0.050
7	-0.200	0.300	0.020	0.000	0.020	0.020
8	0.000	0.002	0.003	0.000	0.020	0.010
9	-0.050	0.100	0.003	0.000	0.010	0.001
10	0.000	0.001	0.001	0.000	0.005	0.001
11	-0.020	0.020	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000
13	0.010	0.010	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.000

The resulting proposed specifications have been provided in form of tables to readily usable by magnet designer and for further analysis.

Table 3: Proposed Specifications for the Field Quality of the 105 mm D2 at Injection Based on the Existing D2 at $\mathbf{R_r} = \mathbf{22\ mm}$ ($\sim 17 \cdot 105/80$ mm)

n	b_m	b_u	b_r	a_m	a_u	a_r
1	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	4.000	1.000	0.000	1.600	1.000
3	-7.000	3.500	0.840	0.000	0.620	0.140
4	0.000	0.050	0.040	0.000	0.210	0.240
5	1.000	0.500	0.150	0.000	0.050	0.020
6	0.000	0.010	0.010	0.000	0.040	0.030
7	0.000	0.010	0.010	0.000	0.010	0.002
8	0.000	0.002	0.001	0.000	0.003	0.003
9	0.000	0.010	0.005	0.000	0.002	0.001
10	0.000	0.001	0.001	0.000	0.002	0.001
11	0.000	0.016	0.001	0.000	0.000	0.001
12	0.000	0.000	0.001	0.000	0.000	0.001
13	0.000	0.000	0.001	0.000	0.000	0.001
14	0.000	0.000	0.001	0.000	0.000	0.001
15	0.000	0.000	0.001	0.000	0.000	0.001

Table 4: Proposed Specifications for the Field Quality of the 90 mm Q4 and 70 mm Q5 Base at Injection Based on the Existing MQY to be Taken at $\mathbf{R_r} = \mathbf{22\,mm}$ ($\sim 17 \cdot 95/70$ mm) and $\mathbf{R_r} = \mathbf{17\,mm}$, Respectively

n	b_m	b_u	b_r	a_m	a_u	a_r
1	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.940	1.100	0.000	0.500	0.900
4	0.000	0.260	0.250	0.000	0.230	0.480
5	0.000	0.080	0.170	0.000	0.070	0.160
6	-3.000	3.000	0.860	0.000	0.140	0.080
7	0.000	0.020	0.040	0.000	0.020	0.040
8	0.000	0.030	0.040	0.000	0.030	0.040
9	0.000	0.010	0.010	0.000	0.010	0.010
10	0.000	0.300	0.080	0.000	0.010	0.010
11	0.000	0.020	0.030	0.000	0.020	0.030
12	0.000	0.020	0.010	0.000	0.020	0.010
13	0.000	0.020	0.010	0.000	0.020	0.010
14	0.000	0.050	0.010	0.000	0.020	0.010
15	0.000	0.020	0.010	0.000	0.020	0.010

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