LHC IR Upgrade: Dipole First with Chromaticity and Dynamic Aperture Issues [*]

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Abstract

A dipole first layout for the LHC interaction region upgrade, while offering a potential reduction of the limitations due the long range beam-beam collisions, charged debris with respect to the quadrupole first layout, presents an enhancement of the chromatic and geometric aberration due large β values in the triplet. These two effects are studied in the following for the dipole first option presented in [1].

INTRODUCTION

The aim of the LHC luminosity upgrade is to increase the luminosity from $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by increasing the number of protons per bunch, increasing the number of bunches, reducing the longitudinal beam size and reducing β^* by upgrading the insertion region [2].

The upgrade of the interaction regions (IR) of the main experiments ATLAS and CMS (IR1 and IR5 respectively) is expected to provide a β^* of $25\mathrm{cm}$ increasing the luminosity by a factor 2 together with a reduction of the longitudinal beam size.

A possible layout for the upgrade of the interaction regions, called dipole first, consists in installing the separation recombination dipoles just after the detector. The final focus (e.g. a triplet) can use two separated channel but it needs to be installed at a greater distance from the IP.

The spectrometer effect of the separation recombination dipoles, together with a proper designed absorber, allows a potential gain in the shielding efficiency for the upstream elements. Due the earlier separation of the beam, the long range beam-beam interactions are reduced. The two separated magnetic channels in the quadrupoles allow the installation of separated correctors for each beam which allow a more effective correction compared to a common magnetic channel as in the quadrupole first design. The aperture of the quadrupoles are used more efficiently since the crossing scheme can be implemented upstream.

The main disadvantage of dipole first layouts is the increase of the aberration due the increase of the maximum β resulting from a larger distance of the final focus from the IP. Moreover the neutral debries requires an additional shielding because they are not deflected and the triplet magnets does not offer a central hole.

This article presents studies of the chromatic effects and long term stability for the dipole first layout presented in [3] and [1] and [4].

The results of these studies can be extrapolated for other upgrade proposals which share a comparable maximum β function.

LAYOUT

The new layout has been designed to maintain all the LHC parameters, all the elements but the triplets and the separation-recombination dipoles in order to keep the cost of the upgrade as low as possible. It turned out that Q5, which is not a wide aperture magnet, needs to be replaced due to larger mechanical aperture requirements. The new magnets require a new technology, such as Nb3Sn superconductor material which offers higher peak field in the coils compared to NbTi magnets. The requirements for the aperture are 10σ separation of the two beams in order to keep the beam beam interaction small, and 9σ from the beam pipe to avoid the beam losses like in the present LHC. The radiation heat load and radioactivity issues, though quite important for a realist design, have not been taken into account and will be addressed in further studies.

Figure 1 shows the upgraded part of the interaction region.

Table 1 shows the main specification of the magnets.

Figure 2 shows the collision optics of the full interaction region.

For a detailed description of the layout and beam-parameters refer to [1];

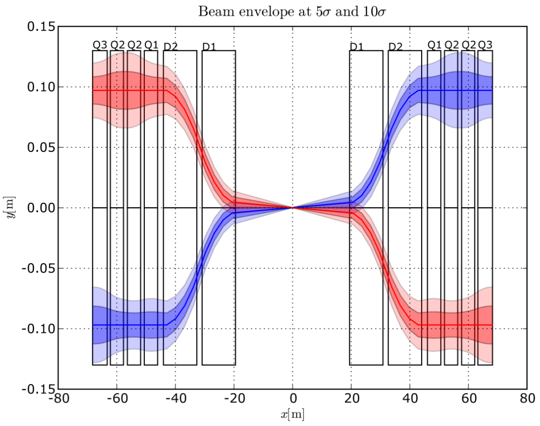

Figure 1: Dipole first layout. D1,D2 are the separation recombination dipoles, Q1,Q2,Q3 the triplet magnets. The blue and red regions represent the envelope of Beam 1 and Beam 2 at 10σ (lighter shade) and 5σ (stronger shade).

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[*] Work supported by CERN and EPFL

Mag.	Pos.	Length	Field	Inner D.
D1	19.45m	11.4m	15.0T	0.130m
D2	32.653m	11.4m	15.0T	0.080m
Q1	46.05m	4.5m	231.0T/m	0.080m
Q2A	51.87m	4.5m	-256.6T/m	0.080m
Q2B	57.69m	4.5m	-256.6T/m	0.080m
Q3	63.25m	5.0m	280.0T/m	0.080m

Table 1: Dipole first magnet specifications.

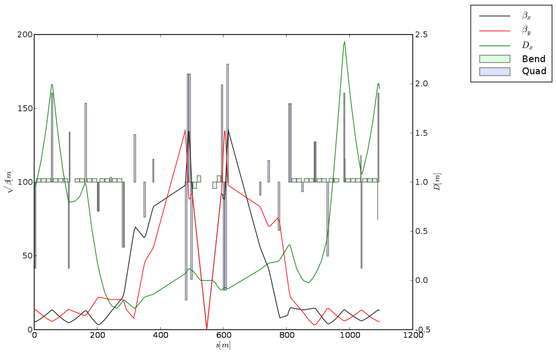

Figure 2: Beam 1 collision optics for the dipole first layout. The boxes in blue represent the quadrupoles and their height is proportional to the gradient. The green boxed represent the bending magnets and their height is proportional to the bending field.

CHROMATICITY

In the LHC the chromaticity at collision (tune dependence on the particle energy) is dominated by the low-β insertion.

The LHC has lattice sextupoles for correcting the chromaticity. For each of the 8 arcs in the LHC there are:

- two focusing sextupoles families ($B_{max} = 1.280$T at 17mm),
- two defocusing sextupoles families ($B_{max} = 1.280$T at 17mm),
- one spool piece sextupoles family ($B_{max} = 0.471$T at 17mm).

These elements can be used for correcting the first and second order chromaticity and the off-momentum beta-beat. Their impact on the the long term stability is minimized because they are interleaved and at π phase advance.

Figure 3 shows the chromaticity after correction. In the first case, using the focusing and defocusing families together, only the linear part can be corrected. In the second case, when the families can individually powered, also the second order term can be corrected. The remaining variation is a third order dependence from the energy which reduces the operational margins and possibilities for chromaticity measurements.

Figure 4 shows the required corrector strengths for the correction. Only around the 70% of the budget is used allowing margins for $beta$-beat corrections.

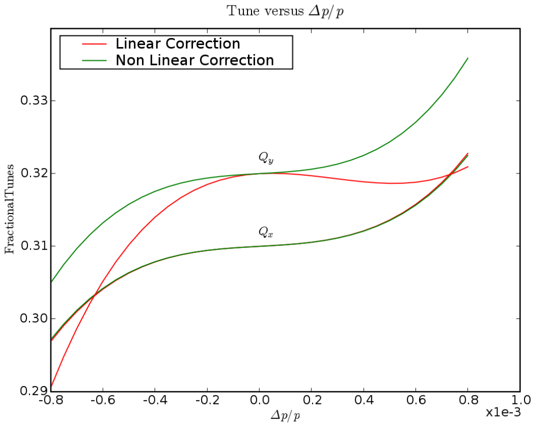

Figure 3: Chromaticity of Beam 1 when linear and second order chromaticity is corrected. For Q_x the second order term is already small thus the red and green curves overlap.

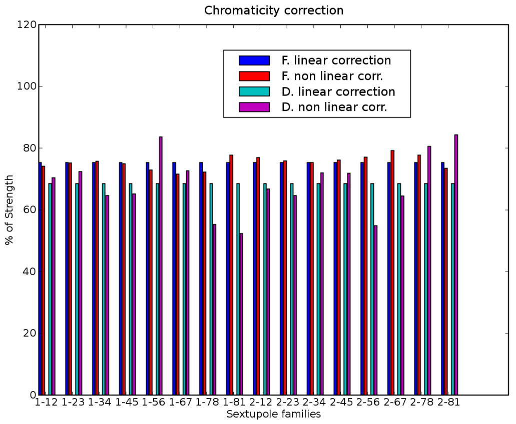

Figure 4: Arc sextupoles strengths required for the linear and second order chromaticity correction. On top of the arcs families also 70% of the spool pieces are used.

An attempt to correct the chromaticity with local sextupoles in the triplet failed due to the large geometric aberrations from the strong sextupolar field required for the correction. These components could be compensated by another set of families located where dispersion vanishes and at pi phase advance, but there are no suitable places for their installation. The sextupolar field in the triplet can be reduced by locally increase the dispersion, but the nonlinear dispersion emerging from the process spoils the efficiency of the local compensation.

DYNAMIC APERTURE (DA)

The dynamic aperture (DA) is estimated by tracking a particle distribution 10^5 turns in 60 realizations of the machine compatible with the error statistics.

The minimum of those 60 computed DAs should give the real dynamic aperture of the machine within a factor of 1.5 (see the LHC design report [5]). A simulated DA of 9σ is therefore satisfactory because the beam-beam interactions and the collimators will limit the aperture to 6σ anyway.

At collision the DA is dominated by the field quality of the elements in the high β regions: in the quadrupole first designs by the triplets quadrupoles and in the dipole first designs by the triplets and the separation/recombination dipoles.

The parameter space for a strict specification of the field quality is too large to be explored systematically.

For a first estimation, the DA has been calculated including field errors only in the triplet. Including field errors of the separation-recombination dipoles, while having an important effect on the DA, increases enormously the parameter space and makes difficult to extend the results to different layouts for which the beta function in these elements is not as large. If not differently stated, the D1/D2 field errors are not included.

The field errors of the rest of the machine should not have a big impact on the DA.

In the studies both IPs are in collision, no multipole error correction was applied and the beam-beam effect is not included. It has been assumed that each magnet of the triplet follows the same statistic.

The parameter space has been probed by, using the field quality of existing magnets with different scaling laws and using a multipole by multipole scan.

DA from measured errors

The present magnet production is used as a reference for the field quality in the tracking studies. The present MQXB is used as prototype for a high gradient quadrupole and the present MQY is used as prototype for a large aperture quadrupole.

Two different scaling laws for the multipole errors are applied. The first is a uniform scaling. The second is expressed by the law

$$b_n(d_1) = (d_0/d_1)^n b_n(d_0) \tag{1}$$

where $b_n(d_1)$ is the relative multipole error of order n ($n = 0$ is a dipole) for a magnet of aperture d_1 and the $b_n(d_0)$ is the relative multipole error for a magnet of aperture d_0. The reference radius of $b_n(d_1)$ and $b_n(d_0)$ is the same. This law ([**?**]) takes into account the geometric scaling of the relative multipoles and the coil precision which does not scale.

Figures 5-9 show the field quality used for several tracking studies and the resulting DA.

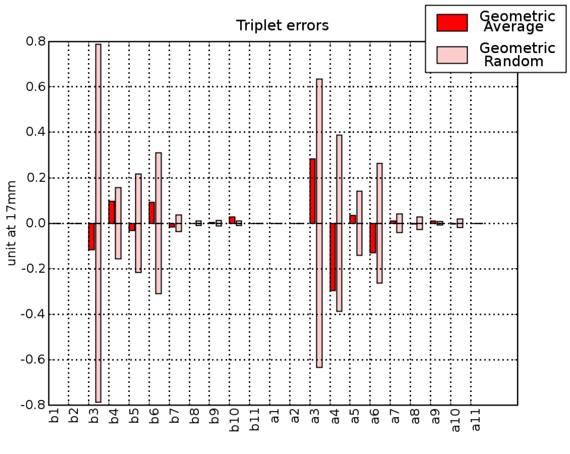

Figure 5: Triplet field quality used for the tracking studies. It is equivalent to the present production of the MQXB. The resulting DA is 3σ.

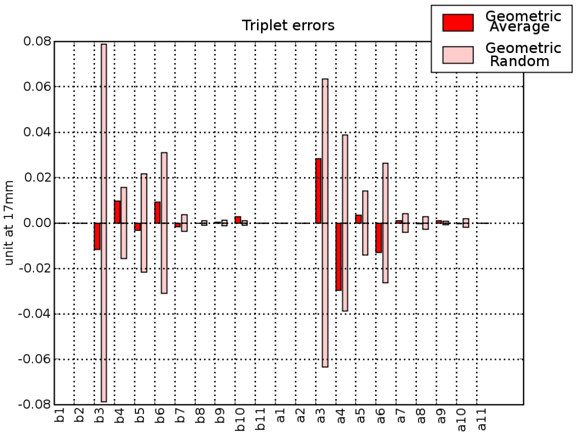

Figure 6: Triplet field quality used for the tracking studies. It is equivalent to the present production of the MQXB uniformly scaled by 10%. The resulting DA is 8.3σ.

Multipole by multipole analysis

An upper bound on the minimum DA can be found by probing one multipole error at the time.

The DA follows a simple scaling law ([6]) when there is a single multipole error in a machine:

$$\log(da_n) \sim -\frac{1}{n-2}. \tag{2}$$

Figure 10 and 11 show the dependance of the DA from the multipole strength where the multipole strength is expressed in term of relative multipole errror at two different reference radius.

The curves reproduce the theoretical scaling law. The plot looks more natural when the reference radius is $12\sigma \simeq$ 34mm.

The multipoles b6, b8, b10 are dominant and the same effect is observed in the simulation for the nominal LHC.

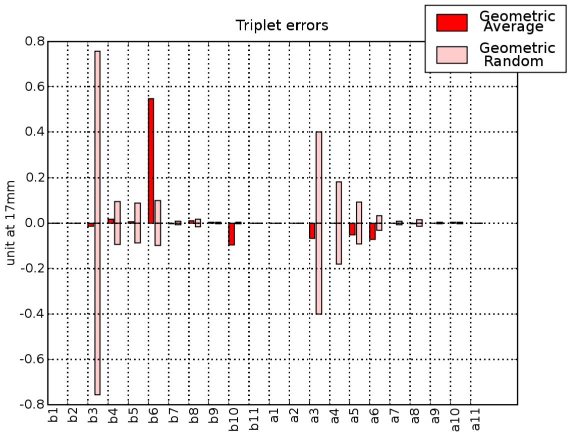

Figure 7: Triplet field quality used for the tracking studies. It is equivalent to the present production of the MQY scaled by law 1. The resulting DA is 2σ.

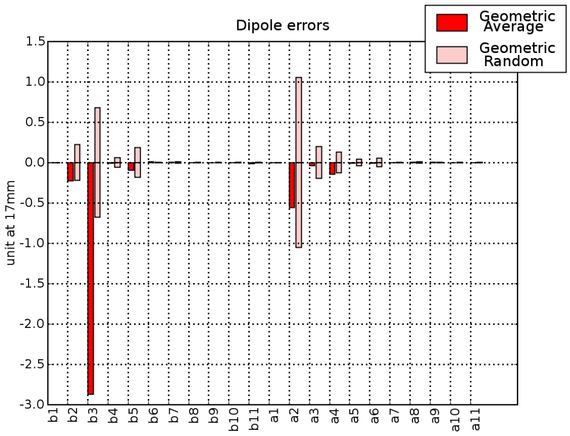

Figure 8: Separation recombination dipole field quality used for the tracking studies. It is equivalent to the present production of the cold D2. The triplets has the field quality of the MQXB as showed d in the figure 5. The resulting DA is 0.8σ.

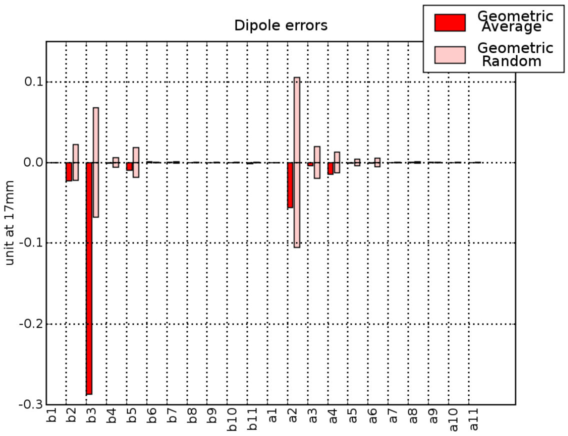

Figure 9: Separation recombination dipole field quality used for the tracking studies. It is equivalent to the present production of the cold D2 uniformly scaled by 10%. The triplets has the field quality of the MQXB uniformly scaled by 10% as showed in the figure 6. The resulting DA is 6σ.

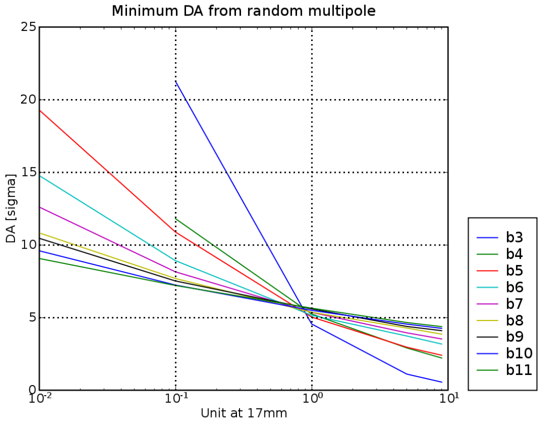

Figure 10: DA when only a multipole is active as function of the multipole errors.The reference radius is 17mm.

A tracking study where all the multipoles are set to 1 unit at 34mm reference radius has been performed and the results shows the combination of the effects of the single multipoles.

As comparison the DA of the nominal LHC without multipole error correction is 13σ.

CONCLUSION

A dipole first scenario with the relevant optics configuration has been developed. The required aperture is compatible with the element specifications. Q5 should be replaced with an MQY magnet type. The crossing schemes are completely managed by D1/D2 and there is no dispersion mismatch due the crossing angle.

The linear and second order chromaticity can be corrected by the sextupoles in the arcs. The third order chromaticity is a limit for the operational margins (i.e. chromaticity measurement). The off-momentum beta-beat is under control in the triplet but not in the arc. It should be possible to compensate it using the available budget of sextupole strength.

The field quality of the present magnet production alone cannot assure the required DA. The better field quality expected from a large aperture does not help. b3 seems responsible for lowest DA but scales quickly. b6, b8, b10 scale slowly and might represent a bottle neck. The multipole errors should be smaller than 1 unit at 34mm for upgrade scenarios where the maximum beta function is larger than 18km. An effective corrector package is needed to reach the required DA.

The radiation damage due the debris has not been addressed yet. The layout allows a natural magnetic TAS

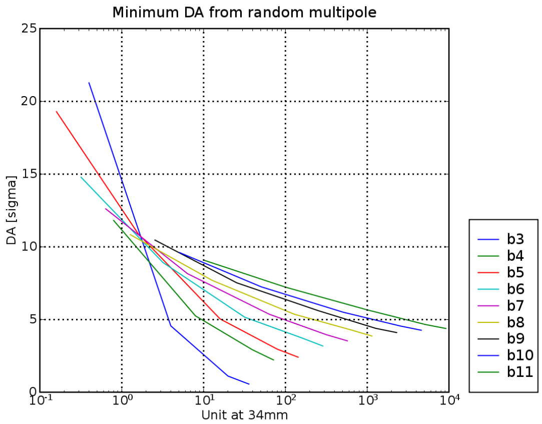

Figure 11: DA when only a multipole is active as function of the multipole errors.The reference radius is 34mm.

Figure 12: Triplet field quality used for the tracking studies. It is equivalent to 1 unit at 34mm reference radius. The resulting DA is 4.5σ.

(racetrack magnets) for the charged debris. It is not clear how to cope with neutral debris. These items will the subject of next studies, as well as the sensitivity of the closed orbit due triplet misalignment, tune modulation due current ripples.

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