Linear Imperfections and Operational Aspects Induced by the D1 Multipole Errors for the LHC Upgrade Phase I

Bernhard Holzer, Stephane Fartoukh

Abstract

In addition to the dynamic aperture as a general machine parameter that has to be optimized in the LHC upgrade machine, strong lower order multipoles will lead to a series of problems for the operation of the machine. A direct influence on the linear beam optics (beta beating, tune shift and coupling) from the $a_2$, $b_2$ multipoles is evident. Equally important however are the multipole coefficients of the next higher order $n=3$ via the feed down effect. The foreseen half crossing angle of about 205 $\mu$rad at the IP creates large offsets in the D1 magnet that finally lead again to a strong $a_2$, $b_2$ errors. The estimates presented in this paper show a distortion in the order of several percent for the beta beat and a considerable shift of the working point. Even after compensation of these effects an influence on the machine performance is expected during machine operation and a further reduction of the multipole coefficients, especially in the case of the D1 magnet, might be needed.
INTRODUCTION

The layout of the interaction region (IR) for the new LHC upgrade project [1] is based on a number of new magnets that will provide the required strengths to focus the colliding beams as well as to separate them after the collision. As in the nominal LHC, a triplet of quadrupole magnets is foreseen for the upgrade optics and - as close as possible to this - a separator dipole (“D1”) to limit the number of parasitic bunch crossings of the two counter rotating bunch trains. Due to the smaller beta function at the IP however the requirements for the free aperture of these IR magnets are more demanding and the effect of the higher order multipoles is more severe than under the nominal LHC conditions. The investigation of these effects normally is done via tracking simulations and the key parameter is the dynamic aperture that results from the given multipole contributions of the magnets. These considerations have been done also for the new IR of the LHC upgrade and an example of the dynamic aperture obtained so far is shown in Fig 1.

![Dynamic aperture of the LHC upgrade in collision optics](image)

Figure 1: Dynamic aperture of the LHC upgrade in collision optics: The two curves compare the situation before optimisation of the multipole coefficients and without correction scheme (red curve) and the new target error table target_10 that refers to a higher magnet field quality combined with a correction scheme for the lower order multipoles (green curve).

The plot refers to the multipole errors that are expected for the new magnets (MQXC/ D1) without any correction and compares the situation with an improved field quality and local correction of the lower order multipoles of these magnets, using a skew quadrupol magnet (a2-corrector), as well as correction coils for the a3,b3,a4,b4 and b6 multipoles.

The effect is considerable and underlines at the same time the need of a local multipole correction scheme and the requirement to minimise the multipole errors in the new IR to reasonable values.

However beyond the pure dynamic aperture as a measure of the global well-being of the beam, the influence of the multipole errors on the operational aspects of the upgrade LHC is of equal importance. Mainly the strong lower order multipoles n = 2, 3 of the D1 magnet will have an influence on the beam operation as they will lead to coupling, tune shifts and distortions of the beam optics (so called “beta beat”) and might even change during beam operation. The direct effect of the n=2 error is obvious as it acts like a quadrupole lens that distorts the linear beam optics. But as a strong crossing angle will be applied at the IP, the resulting large beam offsets in the D1 magnet will create feed down effects from the higher order multipoles (mainly b3 and a3) that distort the beam parameters and that are too large to be neglected.

The baseline for the considerations here is the so called error table target_10 that had been established according to dynamic aperture requirements [2]. It reflects the present understanding of the magnet field quality that is required in the triplet quadrupoles and the D1 separator dipole to obtain sufficient dynamic aperture in the new machine.

Table 1 shows the multipole coefficients as summarised in this target error table for the D1 magnet. Here we follow the usual definition for the so called normal and skew multipole coefficients:

\[
B_y + iB_x = B_{ref} \ast \sum_{n=1}^{\infty} \left( b_n + i a_n \right) \left( \frac{x + iy}{r_0} \right)^{n-1}
\]

B_{ref} corresponds to the main (i.e. dipole) field and the reference radius for the upgrade magnet has been chosen to r_0 = 40 mm. The error table presented here refers to the present requirements for the triplet and D1 multipole tolerances that result from dynamic aperture studies and it acts as a reference for the calculations in this paper.
Table 1

Multipole coefficients of the D1 separator dipole: The values refer to a reference radius of 40 mm and describe the situation as required from dynamic aperture studies for beam collision at 7 TeV (so called error_target_10).

| bn in collision (7500A) | b1M_MBXAB_col := 0.0000 ; b1U_MBXAB_col := 0.0000 ; b1R_MBXAB_col := 0.0000 ; | b2M_MBXAB_col := 0.0000 ; b2U_MBXAB_col := 0.5000 ; b2R_MBXAB_col := 0.6000 ; | b3M_MBXAB_col := 0.0000 ; b3U_MBXAB_col := 1.5000 ; b3R_MBXAB_col := 0.5000 ; | b4M_MBXAB_col := 0.0000 ; b4U_MBXAB_col := 0.2000 ; b4R_MBXAB_col := 0.1000 ; | b5M_MBXAB_col := 0.0000 ; b5U_MBXAB_col := 0.5000 ; b5R_MBXAB_col := 0.1000 ; | b6M_MBXAB_col := 0.0000 ; b6U_MBXAB_col := 0.0500 ; b6R_MBXAB_col := 0.0200 ; | b7M_MBXAB_col := -0.2000 ; b7U_MBXAB_col := 0.3000 ; b7R_MBXAB_col := 0.0200 ; |
| an in collision (7500 A) | a1M_MBXAB_col := 0.0000 ; a1U_MBXAB_col := 0.0000 ; a1R_MBXAB_col := 0.0000 ; | a2M_MBXAB_col := 0.0000 ; a2U_MBXAB_col := 1.5000 ; a2R_MBXAB_col := 1.7000 ; | a3M_MBXAB_col := -1.0000 ; a3U_MBXAB_col := 1.0000 ; a3R_MBXAB_col := 0.3000 ; | a4M_MBXAB_col := 0.0000 ; a4U_MBXAB_col := 0.3000 ; a4R_MBXAB_col := 0.4000 ; | a5M_MBXAB_col := 0.0000 ; a5U_MBXAB_col := 0.1000 ; a5R_MBXAB_col := 0.0500 ; | a6M_MBXAB_col := 0.0000 ; a6U_MBXAB_col := 0.1000 ; a6R_MBXAB_col := 0.0500 ; | a7M_MBXAB_col := -0.0000 ; a7U_MBXAB_col := 0.0200 ; a7R_MBXAB_col := 0.0200 ; |

As the luminosity (or collision-) optics is relevant here, we refer in table 1 only to the values at full excitation of the magnet. The complete error table can be found in the LHC upgrade data base [3].

The main quality issues of concern in the context of operational aspects are the lower order multipoles that refer to the uncertainty error and the random distribution of the corresponding multipole of order n = 2, 3 and that are stronger by about an order of magnitude as the higher order harmonics. It has to be pointed out in this context, that the coefficient describing the random error represents in reality the rms value of a Gaussian distribution of 3 sigma. All considerations in this note therefore refer to a worst case situation where we consider the maximum deviation from an ideal magnet in the sense that the numerical values of the multipole error are obtained for an overall coefficient of $b_{total} = bU + 3*bR$. This might indeed look pessimistic but according to the definition of the measured coefficients in table 1 such a situation can nevertheless occur in the machine.

PARAMETER TABLE OF THE D1 MAGNET

The D1 separator dipole as foreseen for the LHC upgrade phase 1 project is a 7.4 m long
super conducting dipole magnet that will be used to separate the two beams after collision and guide them into their corresponding vacuum chambers. The design of this DX magnet has originally been optimised and used for the RHIC collider ring at BNL. The separator dipole magnet D1 foreseen in the LHC upgrade will consist out of two DX dipoles combined in one cryostat. The main parameters of the DX are listed in table 2:

**RHIC DX magnet:**

![Diagram of RHIC DX magnet]

**Table 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold bore</td>
<td>180 mm</td>
</tr>
<tr>
<td>Warm bore</td>
<td>163/174 mm</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>3.7 m</td>
</tr>
<tr>
<td>Operating temp</td>
<td>4.5 K</td>
</tr>
<tr>
<td>Field</td>
<td>4.4 T</td>
</tr>
<tr>
<td>Current</td>
<td>6.8 kA</td>
</tr>
<tr>
<td>Stored energy</td>
<td>1100 kJ</td>
</tr>
<tr>
<td>Inductance</td>
<td>49 mH</td>
</tr>
</tbody>
</table>

**DIRECT EFFECTS OF THE b2 COMPONENT**

The effect of a b2 component in the D1 magnet can be treated like any other (normal) quadrupole error in the lattice and will lead in first order to a tune shift and a beta-beat. If the quadrupole error is referred to Δk, the resulting change of the machine tune is given as:

$$
\Delta Q = \frac{1}{4\pi} \int_0^1 \beta \Delta k \, ds
$$

where β refers to the beta function at the location of the D1 magnet. At the same time a distortion of the beam optics is created, i.e. a change of the beta function itself, described in general as a relative error \(\Delta \beta / \beta\) whose size is determined as:

$$
\frac{\Delta \beta(s)}{\beta(s)} = \frac{1}{2\sin(2\pi Q)} \int \beta(\tilde{s}) \Delta k(\tilde{s}) \cos(2[\phi(\tilde{s}) - \phi(s)] - 2\pi Q) \, d\tilde{s}
$$

Given the multipole error b2 as indicated for the D1 magnet in table 1, the magnetic field at the reference radius is obtained via

$$
B_0 = B_s * \frac{r}{r_0}
$$

and for the normalised field error Δk that is relevant for the beam optics we get

$$
\Delta k = \frac{\partial B}{\partial r} \left( \frac{1}{B_0} \right) = \frac{1}{B_0} \left( \frac{1}{r_0} \right)
$$

As we consider here the situation during luminosity operation, the required integrate field strength of the D1 is \( \int B \, dt = 30 \, \text{Tm} \) and for the given magnet length of 7.4 m we refer to an absolute D1 field of \( B_0(\text{D1}) = 4 \, \text{T} \) and a beam rigidity for a 7 TeV proton beam. The resulting normalised gradient error due to the b2 coefficient in the D1 therefore is

$$
\Delta k = \frac{4 \times 10^{-4} \times 2.3 \times 10^{-4}}{2.3 \times 10^{-7} \times 40 \times 10^{-3} \times 1 \times 10^{-6}} = 1 \times 10^{-6} \frac{1}{m^2}
$$

which can be used to calculate the tune shift and beta-beat according to the equations mentioned above. The effect of this error on the beam optics is calculated, assuming a maximum beta function at the location of the new D1 magnet of \( \beta_{\max} \approx 10 \, \text{km} \) (worst case for a given plane) and we get accordingly for the tune shift and the beta-beat:

$$
\Delta Q = \frac{1}{4\pi} \beta \Delta k l = \frac{1 \times 10^{-6} / m^2 \times 7.4 \, \text{m} \times 10000 \, \text{m}}{4\pi}
$$

$$
\Delta Q \approx 5.8 \times 10^{-3} \quad \text{per D1 magnet, and}
$$

$$
\frac{\Delta \beta}{\beta} \approx \frac{1 \times 10^{-6} / m^2 \times 7.4 \, \text{m} \times 10000 \, \text{m}}{2 \sin(2\pi Q)}
$$

$$
\frac{\Delta \beta}{\beta} \approx 4 \% \quad \text{per D1 magnet}
$$

In the opposite transverse plane or due to the mirror symmetry of the LHC lattice on the opposite side of the IP this effect is scaled by the size of the beta function and for a value of
\[ \beta \approx 4 \text{km} \] the corresponding values are \( \Delta Q = 2.3 \times 10^{-3} \) and \( \Delta \beta/\beta = 1.6\% \).

### FEED DOWN EFFECTS FROM THE b3 COMPONENT AND A HORIZONTAL CROSSING ANGLE

As in the case of the \( n=2 \) multipoles, that have a direct impact on the beam optics, the next order coefficients \( n=3 \) have to be considered in case of a large beam offset in these magnets due to feed down effects to obtain the overall effect on the beam optics. For the upgrade LHC the half crossing angle of the two beams at the interaction point has to be increased from \( \Phi = \pm 145 \mu \text{rad} \) to at least \( \Phi = \pm 205 \mu \text{rad} \) with respect to the D1 magnet axis to avoid too many parasitic encounters of the circulating bunches. Assuming a symmetric situation of the two beams within the IR therefore each beam will pass through the inner triplet quadrupoles and the D1 separator magnet with a large offset. In addition, in the plane of bending the D1 dipole itself will deflect the beams and contribute to this offset. Accordingly for the considerations in this note we assume a maximum amplitude of the beam of \( \Delta x \approx 15 \text{mm} \). In analogy to eq (1) the magnetic B-field at the reference radius \( r_0 \) created by a normal sextupole component \( b_3 \), is

\[
B = B_0 \cdot b_3 \left( \frac{r}{r_0} \right)^3
\]

resulting in a normalised sextupole strength \( k_2 \) of

\[
k_2 = \frac{\partial^2 B}{\partial r^2} \frac{1}{B \rho} = 2B_0 b_3 \frac{1}{r_0^2} \frac{1}{B \rho}
\]

In the presence of a beam offset this creates an integrated quadrupole error of

\[
k_{q,L} = \frac{2B_0 b_3 \Delta x L}{r_0^2} \frac{1}{B \rho}
\]

and for a \( b_3 \) component of \( b_3 = 3 \times 10^{-4} \) as deduced from table 1 we obtain

\[
k_{q,L} = 2.3 \times 10^{-3} \frac{1}{2 \times 10^{-4}} \frac{1}{L} \approx 7.35 \times 10^{-4} \frac{1}{m}
\]

Again we calculate the resulting tune shift and beta beat and get:

\[
\Delta Q = 5.9 \times 10^{-3} \quad \text{and} \quad \frac{\Delta \beta}{\beta} \approx 3.9\% \quad \text{per D1 magnet}.
\]

The effect on the working point and on the beam optics due to the feed down of the \( b_3 \) coefficient in the D1 magnet is practically of the same size as the direct influence due to the \( b_2 \) error.

### FEED DOWN EFFECTS FROM THE a3 COMPONENT AND A VERTICAL CROSSING ANGLE

In completely equivalent way the feed down contribution is calculated in the presence of a skew sextupole contribution combined with a vertical crossing angle. According to table 1 we obtain an overall \( a_3 \) coefficient of

\[
a_3^{\text{total}} = a_3 U + 3 \times a_3 R = 1.9 \times 10^{-3}
\]

and the resulting effect for tune and optics is \( \Delta Q \approx 3.7 \times 10^{-3} \) and

\[
\frac{\Delta \beta}{\beta} = 2.5\% \quad \text{per D1 magnet}.
\]

There are two points that have to be emphasised in this context:

- These values that result from the feed down effect of the \( b_3 \) coefficient are in the same range as the direct influence of the \( n = 2 \) error on the optics and as they are located at the same optical position they will add up.

- The calculations above refer to one D1 separator only. However in each interaction region two dipoles are installed – one on either side of the IP – and the effects of both will contribute to the optical distortions of the machine. Due to the mirror symmetric design of the LHC interaction regions the direct quadrupole error that results from the \( b_2 \) coefficient of the D1 magnet as well as the feed down effect from the \( b_3 \) add up with the same sign. Accordingly the tune shift is doubled as well as the effect on the beta beat as in any long straight section the phase advance from the right hand side of the IP to the left hand side is in good approximation 180 degrees. The correct expression of the beta beat, including the phase information is

\[
\frac{\Delta \beta(s)}{\beta(s)} = \frac{1}{2 \sin(2\Delta Q)} \int_0^{\Delta \delta(s)} \beta(s) \Delta \delta(s) \cos(2\phi(s) - 2\pi) ds
\]

and if we consider the contribution of the two D1 magnets, being apart by 180 degrees, we obtain for the phase terms at the location of the error, i.e. for \( \phi(s) = \phi(s) \)

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Switzerland

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\[
\cos(2\phi(x)) - \phi(s) - 2\pi Q ds + \\
+ \cos(2\phi(x)) - \phi(s) - 2\pi Q ds + \\
= \cos(2\phi(x)) - \phi(s) - 2\pi Q ds + \\
+ \cos(2\phi(x)) + \pi - \phi(s) - 2\pi Q ds
\]

and we have to conclude that the contributions from the two D1 magnets - scaled by the value of the beta function - add up perfectly to the beta beat.

\[
\cos(2(-\pi Q)) + \cos(2(\pi - 2\pi Q)) = 2* \cos(2(-\pi Q))
\]

**COUPLING**

Unlike to the direct effect of the normal coefficients b2 on the tune and beta function the skew components a2 lead to coupling between the two transverse planes. As a measure for the coupling strength in a storage ring usually the minimum tune split is quoted that is determined by the strength of the skew components k_s and the beta functions in the two transverse planes:

\[
c_\perp = \frac{1}{2\pi} \sqrt{\beta_x \beta_y k_s l_q}
\]

(for details refer to e.g. [4]). In worst case, i.e. assuming \(\beta_x = 10\text{km}, \beta_y = 4\text{km}\), we get for the a2 coefficient of table 1:

\[
a_{2,\text{total}} = a2U + 3*a2R = 6.6*10^{-4},
\]

creating a coupling of \(c_\perp = 2.2*10^{-2}\) per D1 magnet.

As before the same problem occurs due to the feed down, here concerning either a vertical offset in a normal sextupole field b3, or vice versa, a horizontal offset in a skew sextupole configuration.

For

\[
b_{3,\text{total}} = b3U + 3*b3R = 3*10^{-4}
\]

\[
a_{3,\text{total}} = a3U + 3*a3R = 1.9*10^{-4}
\]

and a maximum beam offset in the D1 of 15mm in both cases, we get:

\[
\begin{align*}
  c_{.}(b3) &= 7.4*10^{-2} \\
  c_{.}(a3) &= 4.6*10^{-3}
\end{align*}
\]

**SCALING OF MULTIPOLE EFFECTS**

For convenience and as a basis for the ongoing calculations, the effects presented above are summarised here once again in the form of simple scaling rules. We assume that the errors can be compensated by the usual optics correction schemes (beta beat correction, coupling compensation etc) and that as a consequence during machine operation about 30% of the effects will remain as unavoidable contributions. We further assume that – for convenience – the following error tolerances created by the D1 multipoles can be accepted during beam operation: a beta beat of \(\Delta\beta/\beta \leq 1\%\) and a tune shift of \(\Delta Q \leq 0.001\). In the case of the coupling we assume that the a2 coefficient of the D1 magnet should not contribute to the coupling of the machine more than the expected roll angle tolerance of a triplet quadrupole magnet. Given the parameters for the LHC upgrade lattice – gradient of the triplet magnets \(g \approx 120\text{T/m}, \text{length} = 7.74\text{m} – \) and an alignment tolerance for the roll angle of \(\Delta\phi = 0.1\text{ mrad}\) we obtain a contribution to the coupling of the machine which corresponds to a skew quadrupole coefficient in the D1 Magnet of \(a2 = 2.5\) units.

We consider these limits per D1 magnet and per multipole and therefore we would like to emphasize in this context that this assumption does not exclude worst cases where the effect might integrate over the four D1 magnets and might even add up over the \(n = 2,3\) multipoles.

For the given collision optics of the LHC upgrade (assuming as a worst case \(\beta_x=10\text{ km}, \beta_y=4\text{ km}\)) and an offset of the beam in the D1 magnet of 15 mm we obtain the following limits for the multipole coefficients of one D1 magnet:

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Tolerance limits for the lower order multipole coefficients in the D1 magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>multipole</td>
<td>Limits in (10^{-4})</td>
</tr>
<tr>
<td>b2</td>
<td>1.2</td>
</tr>
<tr>
<td>a2</td>
<td>2.5</td>
</tr>
<tr>
<td>b3</td>
<td>1.2</td>
</tr>
<tr>
<td>a3</td>
<td>1.2</td>
</tr>
</tbody>
</table>

We would like to point out in this context that there is a significant difference in the tolerance requirements for the \(n=2\) and \(n=3\) coefficients. Unlike to the influence on the beam due to the a2 and b2 multipoles that represent a constant optical error, the effect of the \(n=3\) multipoles is – via feed down – a function of the actual machine performance and will depend on the beam operation. Therefore, compared to the values of the present error table “target_10”, summarised in table 1 of this paper, a further optimisation of the magnet quality should be considered with a2 and b3 in priority. Should this target not be reached a
sorting of the DX magnets at the level of the D1 assembly looks mandatory.

It might be illustrative to look at these target values for the low order D1 multipole coefficients from a more practical point of view. For this purpose we contrast the values given in table 3 to the magnet parameters of the present LHC. Two different designs for the separator dipole are used in the present LHC lattice: a normal conducting separator dipole “MBXW” located in IP 1 & 5 and a superconducting version “MBX” in IP 2 & 8. As the beam sensitivity for beta beat as well as for the tune shift due to quadrupole errors scales as \( \frac{\Delta \beta}{\beta} \propto \frac{\beta_{\text{rms}}}{r_{\text{ref}}} \), the magnets in the two cases (upgrade and LHC standard lattice) reflect this relation, the multipoles referred to \( r_{\text{ref}} = 17 \text{ mm} \) and \( r_{\text{ref}} = 40 \text{ mm} \) respectively can be compared directly. The numbers are summarised in table 4: On the left

<table>
<thead>
<tr>
<th>Reference radius</th>
<th>target values ( r_{\text{ref}} = 40 \text{ mm} )</th>
<th>sc D1 magnet (MBX) in IR 2 &amp; 8</th>
<th>nc D1 magnet MBXW) in IR 1 &amp; 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_2 )</td>
<td>1.2</td>
<td>-0.4 ... 0.5</td>
<td>-0.1 ... 0.1</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>2.5</td>
<td>-4.2 ... 0.1</td>
<td>-0.3 ... 0.2</td>
</tr>
<tr>
<td>( b_3 )</td>
<td>1.2</td>
<td>-2.1 ... -0.2</td>
<td>-0.6 ... 0.9</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>1.2</td>
<td>-0.4 ... -0.3</td>
<td>-0.03 ... 0.07</td>
</tr>
</tbody>
</table>

The comparison with the presently used separator dipole MBX deserves special notice: According to a scaling rule presented in [5] the multipole contributions of a superconducting magnet scale inversely to its aperture radius. Assuming the layout of the new D1 magnet for the upgrade phase I lattice were based on the design of the presently installed MBX, scaled in aperture from 80 mm to 180 mm, the following multipole errors are obtained and listed in table 5. For a fair comparison here, the reference radius of the two magnets were chosen as one third of the aperture. A new design of the D1 magnet, based on the presently installed MBX dipole and just scaled to the aperture needs of the LHC upgrade beam would – without further improvement of the magnet field quality – already fulfil the required tolerances.

<table>
<thead>
<tr>
<th>target values D1 (aperture 180 mm)</th>
<th>MBX scaled to 180 mm aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{\text{ref}} = 60 \text{ mm} )</td>
<td>( r_{\text{ref}} = 60 \text{ mm} )</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>1.8</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>3.7</td>
</tr>
<tr>
<td>( b_3 )</td>
<td>2.7</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>2.7</td>
</tr>
</tbody>
</table>
A new design of the D1 magnet, based on the presently installed MBX dipole and just scaled to the aperture needs of the LHC upgrade beam would – without further improvement of the magnet field quality – already fulfill the required tolerances.

Finally and for completeness of these considerations we would like to summarise the situation by comparing the original error table of the D1 magnet with the target values that we obtained from tracking calculations and with the values that we have to require due to the considerations discussed in this paper. For clarity we refer again to an overall multipole error of \( n_{\text{total}} = 1^*n_U + 3^*n_R \) and in each case to a reference radius of 60mm (table 6).

Table 6
Comparison of the original D1 error table (~V2, [6]) with the values required due to tracking calculations and operational aspects

<table>
<thead>
<tr>
<th>upgrade-D1 magnet</th>
<th>original error table &quot;~V2&quot; as presented in [6]</th>
<th>target_10 values (dynamic aperture studies)</th>
<th>target values resulting from operational aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>reference radius</td>
<td>60 mm</td>
<td>60 mm</td>
<td>60 mm</td>
</tr>
<tr>
<td>b_2</td>
<td>3.5</td>
<td>3.5</td>
<td>1.8</td>
</tr>
<tr>
<td>a_2</td>
<td>20.3</td>
<td>9.9</td>
<td>3.7</td>
</tr>
<tr>
<td>b_3</td>
<td>14.2</td>
<td>6.8</td>
<td>2.7</td>
</tr>
<tr>
<td>a_3</td>
<td>6.5</td>
<td>4.3</td>
<td>2.7</td>
</tr>
</tbody>
</table>

**RESUME**

In addition to the dynamic aperture as a general machine parameter that has to be optimized in the LHC upgrade machine, strong lower order multipoles will lead to a series of problems for the operation of the machine. There is first of all a direct influence on the linear beam optics (beta beating, tune shift and coupling) that results from the a_2, b_2 multipoles and that is of considerable strength. Of similar importance - via the feed down effect from the crossing angle - are the next higher order multipoles n=3. The foreseen half crossing angle of about 205 µrad creates large offsets in the D1 magnet that finally lead again to a strong a_2, b_2 errors. The estimates presented in this paper show an influence in the order of several percent for the beta beat and a considerable shift of the working point. Even if these contributions could be compensated for a given setting of the machine, the beam operation might suffer from the effect, that changes in beam position or angle at the IP during machine operation, will lead to unwanted side effects via coupling and optic distortions.

It has to be emphasized here that, given an overall budget for optics errors in the LHC of \( \Delta \beta / \beta = 20 \) %, the contribution from the multipole errors \( n = 2 \) and \( n = 3 \) of a single D1 magnet is already 8 % and that these effects add up at least for the two D1 magnets left and right from the interaction point. There is not much safety margin left for additional optics distortions. Even more: After a compensation of these effects that will be needed in any case, the operational aspect of the problem has to be pointed out. We have to expect changes in the beam crossing angle during luminosity operation and experience from other storage rings show that up to 30% variations in the offset at the D1 have to be considered as a realistic number.

Therefore we conclude that as an extension to the multipole tolerances as given in the error table "target_10" additional limits for the \( n=2 \) and \( n=3 \) multipoles have to be observed in the sense that the sum \( b_U + 3b_R \) and \( a_U + 3a_R \) remains within the boundaries given in table 3 of this paper.

Based on a comparison with the existing D1 magnet equipping the present LHC interaction regions, these target multipoles a_2,b_2,a_3,b_3 given for the new D1 magnet shall not be out of reach and we therefore strongly recommend to re-optimise the design of the new D1 separator magnet in order to meet them.
REFERENCES
[3] The LHC Upgrade Data Base afs/cern.ch/eng/lhc/optics/SLHCV1.0/errors/