A LOW GRADIENT TRIPLET QUADRUPOLE LAYOUT COMPATIBLE
WITH NbTi MAGNET TECHNOLOGY AND \( \beta^* = 0.25 \text{m}^* \)

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Abstract

The paper presents a triplet layout option with long (about 100m total triplet length), low gradient (45T/m to 70T/m) quadrupole magnets. Assuming a maximum magnet diameter of 200mm, the peak coil field at the magnet coils still remains below 7T which is still compatible with conventional NbTi magnet technology. The peak beta function inside the triplet magnets reaches 22km and the configuration therefore requires an additional chromaticity correction scheme similar to a dipole first layout option. However, at the same time, the presented solution provides an interesting alternative to a high gradient triplet layout which requires the new Nb3Sn magnet technology.

INTRODUCTION

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

The upgrade of the interaction regions (IR) of the main experiments ATLAS and CMS (IR1 and IR5 respectively) is expected to provide a \(\beta^*\) of 25cm increasing the luminosity by a factor 2.

The present layout, designed for \(\beta^*\) of 55cm, is not able to provide a \(\beta^*\) of 25cm because the triplet quadrupoles can not fulfill the required specifications on mechanical aperture. In addition the lifetime of the triplets is estimated to be limited to 7 years at the nominal luminosity due the radiation [1] coming from the IP. If no relevant changes in the design with respect to the radiation protection is performed, this time is reduced by an order of magnitude at the upgraded luminosity implying a triplet replacement on a year basis.

LAYOUT AND OPTICS

We propose a quadrupole first layout compatible with NbTi technology.

Figure 1 shows the layout and the corresponding beam envelope. Figure 2 and 3 show the collision optics for Beam 1 and Beam 2.

Table 1 summarizes the main quantities of the layout.

The triplet magnets are highly optimized for aperture or low peak field (max 4.2T/m) in order to cope with the radiation coming form the IP (high temperature margin or room for internal shielding).

The presence of dispersion in the triplet can be used for a local chromaticity correction.

CHROMATICITY

For the LHC the energy acceptance of \( \frac{\Delta\beta}{\beta_0} = \delta = 0.8 \times 10^{-3} \) has to be preserved.

The chromaticity, tune dependence with energy \( Q(\delta) \), is enhanced by high \( \beta \) values and if not properly corrected can lead to a limitation of the energy acceptance. In particular a positive slope of \( Q(\delta) \) is required in order to avoid the head-tail instability.

In the LHC there are two interleaved sextupoles families per arcs (MS) and a family of spool pieces sextupole
correctors (MCS). They can be used to correct globally the first and the second order chromaticity and the off-momentum beta-beat [2]. An attempt for a local chromaticity correction has been done using sextupole corrector placed in front of the quadrupoles, but it was not successful due the local introduction of non linear chromaticity.

Figure 4 and 5 show the results of different correction options.

Table 1: Specifications of the quadrupole first layout.

<table>
<thead>
<tr>
<th>Mag.</th>
<th>Pos.</th>
<th>Length</th>
<th>Field</th>
<th>Inner D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>21.251m</td>
<td>22m</td>
<td>-40.0T/m</td>
<td>0.12m</td>
</tr>
<tr>
<td>Q2A</td>
<td>45.053m</td>
<td>22m</td>
<td>69.1T/m</td>
<td>0.12m</td>
</tr>
<tr>
<td>Q2B</td>
<td>67.054m</td>
<td>22m</td>
<td>-56.0T/m</td>
<td>0.12m</td>
</tr>
<tr>
<td>Q3</td>
<td>89.055m</td>
<td>22m</td>
<td>15.5T/m</td>
<td>0.12m</td>
</tr>
<tr>
<td>D1</td>
<td>111.056m</td>
<td>13m</td>
<td>8.7T</td>
<td>0.12m</td>
</tr>
<tr>
<td>D2</td>
<td>131.056m</td>
<td>13m</td>
<td>8.7T</td>
<td>0.06m</td>
</tr>
</tbody>
</table>

Table 2 and 3 show the required sextupole strengths.

Table 2: Required strengths of the arc sextupoles for the correction of the linear part of the chromaticity. All focusing and defocusing families respectively equally powered.

<table>
<thead>
<tr>
<th>Family</th>
<th>$k^2_{\text{max}}$</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS Defoc.</td>
<td>0.380m^{-2}</td>
<td>68%</td>
</tr>
<tr>
<td>MS Foc.</td>
<td>0.380m^{-2}</td>
<td>76%</td>
</tr>
<tr>
<td>MCS</td>
<td>0.130m^{-2}</td>
<td>70%</td>
</tr>
</tbody>
</table>

Table 3: Required strengths of the arc sextupoles for the correction of the linear and second order part of the chromaticity. The MS families are individually powered.

<table>
<thead>
<tr>
<th>Family</th>
<th>Average Str.</th>
<th>Max Str.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS Defoc.</td>
<td>69%</td>
<td>102%</td>
</tr>
<tr>
<td>MS Foc.</td>
<td>76%</td>
<td>110%</td>
</tr>
<tr>
<td>MCS</td>
<td>70%</td>
<td>70%</td>
</tr>
</tbody>
</table>

The results shows that the arcs are still able to compensate the chromaticity generated by the high $\beta$ region with margin left for off-momentum beta-beat correction.

**DYNAMIC APERTURE**

The dynamic aperture (DA) of the LHC at collision is dominated by the field quality in the high beta region, that is triplet and separation recombination magnets.

The tracking studies are performed with SIXTRACK using 60 seeds and $10^5$ turns, the target DA for collision is $10\sigma$ ([3]).

In the LHC the triplet is equipped with a corrector package used to minimize the Hamiltonian driving terms which are close to the working point.

Tracking studies for the nominal configuration shows that the minimum DA of LHC without triplet correction is about $13\sigma$. 
The new layout, because of the high beta values, requires a careful definition of the field quality allowed in the triplet and the implementation of a correction scheme.

Tracking studies are on going in order to explore the parameter space (multipole errors) for the definition of the required field quality for this design.

A preliminary study using an ideal machine and the field quality of the present LHC triplet magnets (Figure 6) for the new ones shows that the minimum DA over 60 seeds is about $2.3\sigma$. Scaling by a factor of 10 the triplet errors shows an increase of the minimum dynamic aperture to $7.3\sigma$.

An efficient correction scheme or a better field quality is required to meet the specification of $10\sigma$.

**CONCLUSION**

The present layout shows that the NbTi can be still a viable technology for the IR upgrade. The chromaticity generated by the high beta values can be compensated by the existing sextupoles circuit with margin left for off-momentum beta-beat correction.

The low value for the dynamic aperture may probably be restored to the LHC requirements by a corrector package or a further improvement of the field quality. A tracking campaign for their definitions is on going.

The radiation issues should be solved by the huge margin in aperture that can still be provided by NbTi quadrupoles. The peak field at the coil gives a margin of 50mm in radius to the minimum required aperture. The margin can be used for a shielding layer (which may positively contribute to the final field quality) or for a further optimization of the layout in the direction of lowering the beta function and reducing the magnetic length by increasing the gradient.

Studies for the radiation protection of the magnets, still missing, should give the last confirm for the feasibility of this layout.

**REFERENCES**

