OPTICS AND LATTICE OPTIMIZATIONS FOR THE LHC UPGRADE PROJECT

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Abstract

The luminosity upgrade of the LHC collider at CERN is based on a strong focusing scheme to reach lowest values of the beta function at the collision points. Several issues have to be addressed in this context, that are considered as mid term goals for the optimisation of the lattice and beam optics: Firstly a number of beam optics have been developed to establish a baseline for the hardware R&D, and that will define the specifications for the new magnets that will be needed, in Nb3Sn as well as in NbTi technology. Secondly, the need for sufficient flexibility of the beam optics especially for smallest $\beta^*$ values, the need for a smooth transition between the injection and the collision optics, the comparison of the optics performance between flat and round beams and finally different ways to optimise the chromatic correction, including the study of local correction schemes. This paper presents the status of this work, which is a result of an international collaboration, and summarises the main parameters that are foreseen to reach the HL-LHC luminosity goal.

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INTRODUCTION

The goal of the LHC upgrade project is the production of a total integrated luminosity of approximately 3000 $fb^{-1}$ over the lifetime of the HL-LHC. To achieve this, a considerable reduction of the beta function at the high luminosity Interaction Points (IP) is needed, as values as low as $\beta^*=15$cm are aimed for. The basic concept is based on a Achromatic Telescopic Squeezing (ATS) scheme [1] that has been proposed in this context and that allows both the production and the chromatic correction of very low $\beta^*$ values. This scheme relies essentially on a two-stage approach: First a so-called pre-squeeze optics is established by using exclusively the matching quadrupoles of the high luminosity insertions IR1 and IR5. In a second stage, $\beta^*$ can be further reduced by acting only on the insertions on either side of IR1 and IR5 creating sizable $\beta^*$-beating bumps in the four neighboring sectors. These waves of $\beta^*$-beating create the required $\beta^*$ reduction and at the same time boost, at constant strength, the efficiency of the chromaticity sextupoles located in the sectors 81, 12, 45 and 56. Figure 1 shows the optics for $\beta^*=10$cm which is considered as ultimate limit of a feasible squeeze optics [2]. As can be seen in the plot, the ATS scheme has a strong impact on the optics of both the matching section of the high luminosity IPs but also on the optics of the neighboring LHC sectors. Therefore a large optics investigation has been launched to study the flexibility of the overall upgrade optics, taking into account especially the $\beta^*$ functions at Q4 in IP1/5 where crab cavities will be installed. In addition, beam optics scenarios have to be studied for a variety of different beam optics in the neighboring sectors where special boundary conditions have to be observed in proton as well as heavy ion operation.

![Figure 1: ATS optics with $\beta^*=10$ cm, at IP5: The transverse beam sizes [mm] are plotted between the neighboring sectors IR4 and IR6.](image)

Table 1 summarises the main parameters for the HL-LHC project, compared to the standard LHC design values [3].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC nominal</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_p [10^{13}]$</td>
<td>1.15</td>
<td>2.2</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td>$\beta^* [m]$</td>
<td>0.55</td>
<td>0.15</td>
</tr>
<tr>
<td>$\epsilon_0 [\mu m]$</td>
<td>3.75</td>
<td>2.5</td>
</tr>
<tr>
<td>bunch distance</td>
<td>25ns</td>
<td>25ns</td>
</tr>
<tr>
<td>x-angle [µrad]</td>
<td>300</td>
<td>590</td>
</tr>
<tr>
<td>$L_{\text{peak}}$</td>
<td>$1*10^{34}$</td>
<td>$9*10^{34}$</td>
</tr>
</tbody>
</table>

Based on new supra conducting triplet quadrupoles and depending on the technology that will be available for
these magnets (NbTi / Nb3Sn) gradients between 120 T/m and 170 T/m can be assumed and accordingly a variety of different beam optics has been studied. However not all the boundary conditions (namely the betas in front of Q4) assure the possibility to match the new triplet in the LHC high luminosity interaction regions to the existing arc structure. In order to find satisfying initial boundary conditions, we have scanned the optics values in horizontal and vertical plane at the location of Q4 in a wide range, verifying the possibility to match the generated triplet into the arc structure of the two LHC beams. Figure 2 shows the area in the $\beta_x$ and $\beta_y$ space where an optimal convergence of the matching of the new triplet with the two rings is obtained. It is mainly determined by the constraint imposed by the magnets in the LHC matching sections of the two LHC rings, i.e. Q4 ... Q7 in the interaction region layout - one of the most critical limits being the maximum allowed strength of the Q7 magnet.

The solutions plotted in Figure 2 define the pre-squeeze optics have been studied for different $\beta^*$ values that - for a given optics parameter at the location of the crab cavities - and for a $\beta$-function at the IP of $\beta^*$ = 40cm, the layout of the triplet quadrupoles, following a well-defined strategy [4], is determined. Still however not all the boundary conditions (namely the betas in front of Q4) assure the possibility to match the new triplet in the LHC high luminosity interaction regions. The successful beam optics shown in Fig. 2 are equivalent in terms of maximum beta functions reached in the triplet quadrupoles and natural chromaticity of the lattice. The resulting parameters of the triplet quadrupoles differ only slightly from the pre-defined values in magnet length and maximum feasible gradient of $g=170$ T/m.

In a more detailed approach the beta functions that are achievable in the pre-squeeze optics have been studied: Assuming a gradient in the triplet quadrupoles of $g=170$T/m the convergence of the optics match has been studied for different $\beta^*$ values. Again, the optics at the position of Q4 is included as additional boundary condition. Fig. 3 summarises the results: While a comfortable variety of different beam optics is obtained for the standard value of $\beta^*$=40cm in the pre-squeeze optics, the flexibility of the lattice shrinks if smaller $\beta^*$ values are aimed for and in the extreme case of $\beta^*$=35cm only in a limited number of possible optics is obtained afterwards. Even more severe, only for pre-squeeze optics that guarantee beta values larger than $\beta^*$=37cm, a successful application of the ATS scheme is possible. For the most promising case of $\beta_x$=510m and $\beta_y$=770m at the location of Q4 (see Fig. 2), the properties of the lattice have been studied in more detail:

- The possibility to combine the optics with the ATS scheme to reduce the $\beta^*$-functions from the pre-squeeze values of $\beta^*$=40cm down to the final values of $\beta^*$=15cm,
- the chromatic aberrations
- and finally the impact of the ATS scheme on the neighboring LHC sectors.

Figure 3: Horizontal and vertical beta functions in front of Q4 which lead to the convergence of the matching of the new triplet (170 T/m) with the LHC lattice in the high luminosity interaction regions.

The chromatic aberration in the case of $\beta^*$=15cm is shown in Fig. 4. Considering the nominal LHC momentum spread of $\Delta p/p$=of $1\times10^{-4}$ the curve of Fig. 4 reflects the comfortable momentum acceptance that is obtained.

![Figure 3](image3.png)

**Figure 3:** Horizontal and vertical beta functions in front of Q4 which lead to the convergence of the matching of the new triplet (170 T/m) with the LHC lattice in the high luminosity interaction regions.

![Figure 4](image4.png)

**Figure 4:** Horizontal and vertical tune for the upgrade optics as a function of $p/p$. The figure compares the situation of two alternative triplet gradients.

**OPTICS FLEXIBILITY STUDIES**

The flexibility of the nominal LHC optics is limited in several aspects and attempts to reach smallest $\beta^*$ values are limited by the betatron phase advance from the inner triplet to the arc sextupoles, by the strengths of the matching quadrupole strengths and by aperture needs. To overcome these inherent optical boundaries alternative LHC long straight section (LSS) layouts are studied. The existing lattice, designed to match the optical functions at the collision point to the periodic arc optics, was frozen in the early LHC design and, given the hardware changes associated with HL-LHC, may be upgraded. The goal is to explore the limits of the nominal optics, using a case study of the Q5 and Q6 matching quadrupoles replaced by...
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REFERENCES


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