OPTICS AND LATTICE OPTIMISATIONS 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 β* 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.

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 β^*=15cm are aimed for. The fundamental concept is based on a Achromatic Telescopic Squeezing (ATS) scheme [1] which has been proposed in this context and that allows both the production and the chromatic correction of very low β^* values. This scheme relies essentially on a two-stage approach: First a pre-squeeze optics is established by using exclusively the matching quadru-poles of the high luminosity insertions IR1 and IR5. In a second stage, β^* can be further reduced using only on the insertions on either side of IR1 and IR5 creating sizable β-beating bumps in the four neighboring sectors. These waves of β-beating create the required β^* 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 β^*=10cm 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 β 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.

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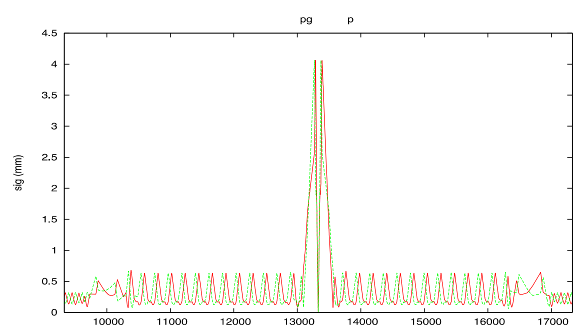

Figure 1: ATS optics with β^*=10 cm, at IP5: The transverse beam sizes [mm] are plotted between the neighboring sectors IR4 and IR6.

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

Table 1: HL-LHC Parameters Compared to the LHC Nominal Values

	LHC nominal	HL-LHC
N_p [10^{11}]	1.15	2.2
n_b	2808	2808
β^* [m]	0.55	0.15
ε_n[μm]	3.75	2.5
bunch distance	25ns	25ns
x-angle [μrad]	300	590
L_{peak}	$1*10^{34}$	$7.3*10^{34}$

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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 acceptable initial boundary conditions, we have scanned the optics values in the horizontal and vertical plane at the location of Q4 in a wide range, thus verifying the possibility to match the generated triplet into the arc structure of the two LHC beams. Figure 2 shows the area in the β_x and β_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 - with one of the most critical limits being the maximum allowed strength of the Q7 quadrupole.

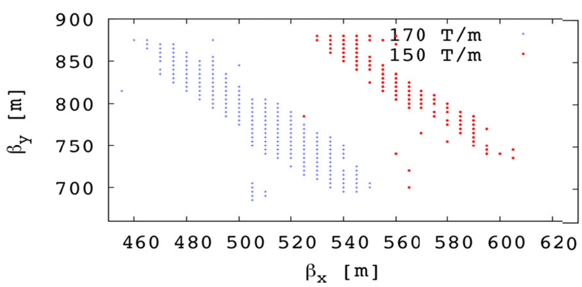

Figure 2: Horizontal and vertical β-functions in front of Q4, which leads to the convergence of the matching. The plot compares the situation of two different triplet gradients.

The solutions plotted in Figure 2 define the pre-squeeze optics in the sense that - for a given optics parameter at the location of the crab cavities - and for a β-function at the IP of β^*= 40cm, the layout of the triplet quadrupoles, following a well-defined strategy [4], is determined. However not all the boundary conditions (namely the betas in front of Q4) allow the possibility to match the new triplet in the LHC high luminosity interaction regions. The successful beam optics shown in Figure 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 β-functions that are achievable in the pre-squeeze optics have been studied: Assuming a gradient in the triplet quadrupoles of g=170T/m the convergence of the optics match has been studied for different β^* 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 β^*=40cm in the pre-squeeze optics, the flexibility of the lattice shrinks if smaller β^* values are aimed for. In the extreme case of β^*=35cm only in a limited number of possible optics is obtained. More severely, a successful application of the ATS scheme is possible only for pre-squeeze optics that allow β*-values larger than β^*=37cm. For the most promising case of β_x=510m and β_y=770m at the location of Q4 (see Fig. 2), the properties of the lattice have been studied in more detail, including:

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

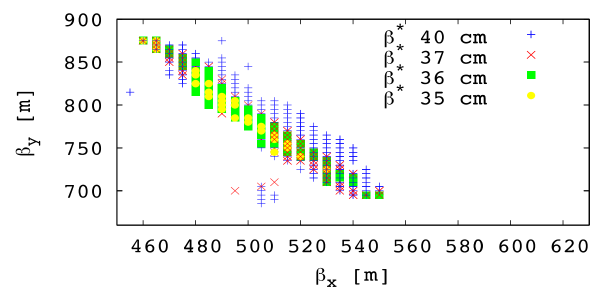

Figure 3: Horizontal and vertical beta functions in front of Q4 which lead to the convergence of the matching of the new triplet (170 T/m) with the LHC lattice in the high luminosity interaction regions.

The chromatic aberration in the case of β^*=15cm is shown in Fig. 4. Given the nominal LHC momentum spread of Δp/p=of $1*10^{-4}$ the curve of Fig. 4 reflects the comfortable momentum acceptance that is obtained.

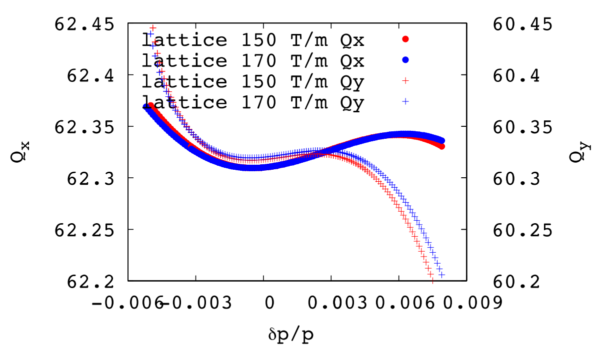

Figure 4: Horizontal and vertical tune for the upgrade optics as a function of Δp/p. The figure compares the situation of two alternative triplet gradients.

OPTICS FLEXIBILITY STUDIES

The flexibility of the nominal LHC optics is limited in several aspects and attempts to reach smallest β^* values are limited by the betatron phase advance from the inner triplet to the arc sextupoles, by the strengths of the matching quadrupoles and by aperture requirements. 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 andQ6 matching quadrupoles replaced by equivalent hardware doublets (the replacement of both is needed to maintain the FODO structure of the LSS). Figure 5 shows a possible resulting LSS optics for this case study. The optical flexibility manifests itself in a lower attainable beta function at the IP, β^*=23cm, without the need of the ATS squeeze technique. In a further step we shall attempt to get highest lattice flexibility by studying all necessary modifications in the existing quadrupoles from Q4-Q7. Based on a standard mini beta scheme in the LHC insertions LSS1 and LSS5 we aim for the target beta* of the HL-LHC project, β^*=15cm.

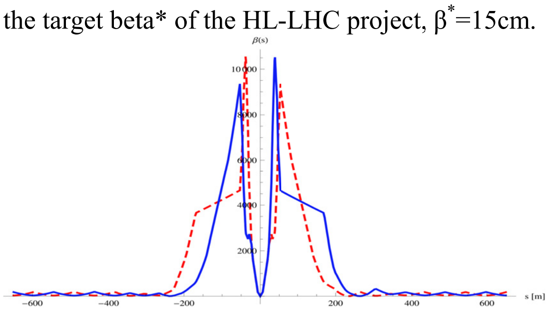

Figure 5: The optics of the long straight section, showing the horizontal (blue) and vertical (red) β-functions as a function of longitudinal distance from IP5, with the matching quadrupoles Q5 and Q6 replaced by doublets.

The study of lattice modifications on a longer time scale includes a new layout of the matching section, in particular replacing each Q5 and Q6 by a doublet (as presented here), reinforcing Q7 by a longer quadrupole and replacing Q4 by a quadrupole triplet.

OPTICS IN NEIGHBORING SECTORS

The beam optics in the neighboring LHC sectors is strongly affected by the ATS scheme. As can be seen in Figure 1, the beta beating wave which is essential to reduce the beta function in IP1 and IP5 and obtain values well below the pre-squeeze optics, is created deliberately in the matching sections of the neighboring sectors. However the optics in these regions may have to obey special boundary conditions. This is notably true in IP2 and IP8 where the high-energy experiments LHCb and ALICE are located and so the low beta insertion has to be kept flexible enough to guarantee successful data taking of these experiments. In an extensive study the optics conditions of these neighboring sectors have been investigated with five different conditions that had been identified:

- β^*=10cm round beam optics in IP1/ β^*=3m in IP8
- β^*=5cm/20cm flat beam optics in IP1/ β^*=3m in IP8
- β^*=20cm/5cm flat beam optics in IP1/ β^*=3m in IP8
- β^*=40cm pre-squeeze optics in IP1/ β^*=50cm in IP8
- β^*=5.5m injection optics in IP1 / β^*=10m in IP8

In addition to the optics requirements at the IPs additional constraints have been taken into account: the same phase advance in beam 1 and beam 2 of LHC and a satisfactory solution for all optics scenarios with the same overall phase advance. To determine the area of satisfactory optics convergence for the first four scenarios, the horizontal and vertical phase advances in LSS 8 have been varied and the optics has been re-matched according to the new boundary conditions. The results are shown on Figure 6. Depending on the optics constraints, acceptable results are obtained for a number of different phase advances across the IR. The area surrounded by the black line indicates the values for which obeying all optics requirements for luminosity operation in IP8 and a common phase advance is achievable.

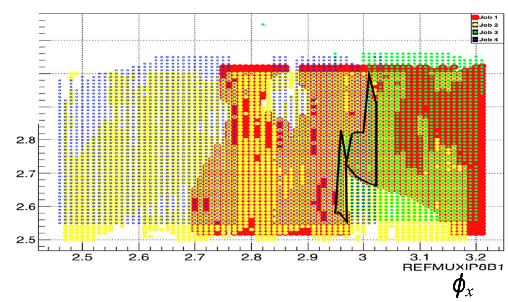

Figure 6: Area of stable phase advance over IR8 that lead to successful optics convergence: For four different scenarios the phase advances are plotted that lead to possible solutions. The black line shows the region where for one common phase all optics conditions can be satisfied.

An example of one of the new optimised beam optics is shown in Figure 7, corresponding to the situation of β^*=3m in IP8 and β^*=10cm in IP1. On the left hand side of the lattice the non-ATS FODO optics is maintained whereas on the right hand side the large β-function values in the arc show the onset of the ATS beta wave.

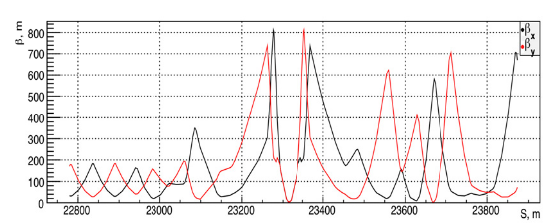

Figure 7: Optical solution for IP8, combining the standard FODO optics (left) with the ATS optics (right of IP).

REFERENCES

[1] S. Fartoukh, Breaching the Phase I Optics Limita-tions for the HL-LHC, LHC performance workshop, Chamonix, 2012.
[2] S. Fartoukh, R. De Maria, MOPPC011, these proc.
[3] O. Bruening: HL-LHC Param. Space and Scenarios, LHC performance workshop, Chamonix, 2012.
[4] R. De Maria, MOPPC010, these proc.

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