OPTICS DESIGN AND LATTICE OPTIMISATION FOR THE HL-LHC*

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Abstract

The luminosity upgrade project of the LHC collider at CERN is based on a strong focusing scheme to reach lowest values of the β function at the collision points. Depending on the magnet technology (Nb_3Sn or Nb-Ti) that will be available, a number of beam optics has been developed to define the specifications for the new superconducting magnets. In the context of the optics matching new issues have been addressed and new concepts have been used that play a major role in dealing with the extremely high beta functions. Quadrupole strength flexibility and chromatic corrections have been studied, the influence of the quadrupole fringe fields has been taken into account and the lattice in the matching section had been optimised including the needs of the crab cavities that will be installed. The transition between injection and low β optics has to guarantee smooth gradient changes over a wide range of β* values and the tolerances on misalignments and power converter ripple has been re-evaluated. Finally the successful combination of the quadrupole strengths in the high luminosity matching sections with those in the neighbouring sectors - a key concept of the ATS - plays an essential role to reach smallest β* values. This paper presents the results obtained within the Hi-Lumi collaboration Task 2.2 [1] and summarises the main parameters of the project.

INTRODUCTION

The goal of the LHC upgrade project is the production of a total integrated luminosity of 3000 fb^{-1}. To achieve this, a considerable reduction of the beta function at the high luminosity Interaction Points (IP) is needed:values as low as β^*=15 cm are aimed for. The concept is based on an Achromatic Telescopic Squeezing (ATS) scheme [2] enabling both the matching of very low β^* optics and the correction of the chromatic aberrations induced (demonstrated last year in LHC [3]). The main parameters for the HL-LHC project are summarised in table 1 and compared to the present design. A key issue for the optics design and the lattice modifications is to establish a smooth matching between the small Twiss parameters at the IP and the periodic arc. New large aperture magnets will be needed in the inner triplet due to the strong beam divergence that is created by the extremely low β* values. Several lattice options and beam optics have been studied and optimised, taking into account the special issues that arise from such an extreme focusing scheme. At present the most promising solution is based on 150 mm aperture Nb_3Sn quadrupoles operating at 140 T/m to replace the present low beta triplet.

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 (10σ)	590 (12σ)
L_{peak} (crab cav)	1.2×10^{34}	2.2×10^{35}

Figure 1 shows the optics for β^*=15 cm which is the design for a feasible squeeze optics [4]. 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 and on the optics of the neighbouring LHC sectors. Therefore a large optics study has been launched to investigate the flexibility of the IR1, 5 upgrade optics, taking into account especially the β functions at Q4 where crab cavities will be installed. In addition, beam optics scenarios had to be studied for a variety of beam optics in the neighbouring IRs where special boundary conditions have to be observed in proton and heavy ion operation.

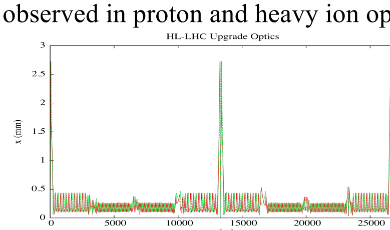

Figure 1: ATS optics with β^*=15 cm, at IP1,5: The transverse beam sizes are plotted, showing the telescopic squeeze, that starts in the two neighboring insertions (IR) on either side of the high luminosity IRs.

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OPTICS OPTIMISATION FOR CRAB CAVITY OPERATION

One of the most crucial features of the HL-LHC upgrade project is the use of crab cavities to compensate for the geometric luminosity loss that is related to the crossing angle of the two beams. Given the luminosity formula, for a limited beam intensity the emittances of the beams and the β*values are the only ingredients available for optimisation:

$$L = \frac{N_1 N_2 f n_b}{2\pi\sqrt{\sigma_{1x}^2+\sigma_{2x}^2}\sqrt{\sigma_{1y}^2+\sigma_{2y}^2}} \times R$$

However a considerable crossing angle will be needed to avoid parasitic encounters of the 25 ns spaced bunches in the machine and establish a 10 σ separation at each parasitic encounter. Accordingly a crossing angle of 590 μrad has to be established at each high luminosity IP. The loss factor R which is related to the hourglass effect but mainly to the geometric effect of the crossing angle, amounts to 0.31 and the installation of crab cavities to compensate this luminosity reduction therefore is indispensable: The beam optics in the new interaction regions had to be optimised according to these needs. Schematically the problem is shown in Fig 2. Before and after each IP, transverse deflecting crab cavities will be installed to create a local shearing of the bunches.

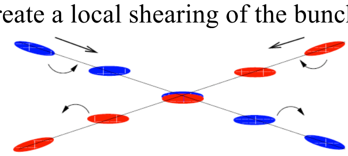

Figure 2: Schematic view of the crab crossing effect.

The required crab voltage depends on the optical functions β at the location of the cavities and at the IP:

$$V = \frac{cp\theta_c}{2e\omega}\frac{1}{\sqrt{\beta^*\beta_{crab}}}$$

As the restricted optics flexibility of the matching section limits the beta functions at the crab cavity location, a new layout has been proposed to reduce the demand on the voltage of the crab cavities, while substantially improving the optics performance towards smaller beta functions at the IP. A number of modifications are proposed, but not yet implemented in the HLLHCV1.0 optics and layout [4], that leads the way to a highly improved situation:

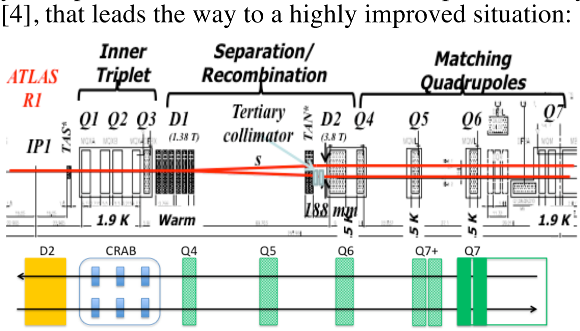

Figure 3: Proposed modifications of the LHC lattice to obtain improved flexibility and β* reach.

Fig 3 shows the LHC lattice in the high luminosity regions, the lower part schematically shows the additional modifications for the crab cavity optimisation: In addition to a modest re-arranging of the matching quadrupoles Q4...6, to obtain a second triplet like structure, an additional quadrupole lens is proposed to support the installed Q7 magnet [5]. The resulting optimised optic is shown in Fig 4.

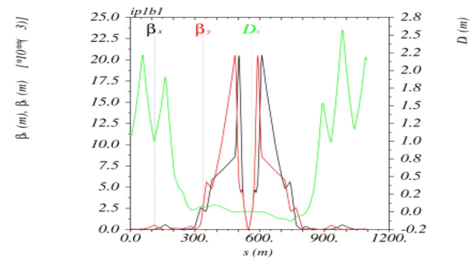

Figure 4: Beam optics in the high luminosity IPs, including improvements for the crab cavity operation.

FRINGE FIELD MODELING

The very small β* values achieved in the new optics design of the HL-LHC requires large apertures in the high gradient final focusing quadrupoles, which lead to considerably stronger fringe field effects compared to the LHC standard magnets. As a consequence a considerable influence is expected on the beam optics, and the magnet model used to describe the machine had to be improved to take these effects into account. The usual magnet model based on a hard edge description causes significant optical errors (Δβ/β). To quantify these errors and improve the quality of the optics calculations, a series of shorter magnets was added in the optics calculations at either end of the magnet with progressively lower values of normalised gradient, keeping constant the overall integral $\int kdl$.

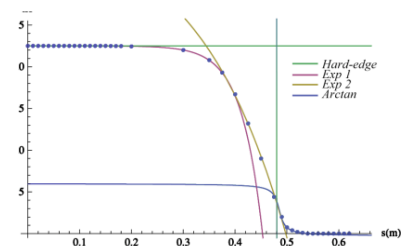

Figure 5: Improved model of the fringe field fall off.

Three functions are used to replicate the fringe field - one arctan function and two exponentials functions, which are fitted to a measured field map to keep the description as close as possible to real field falloff [6]. Taking into account the effect of the two high luminosity regions in HL-LHC, the re-calculated optics shows a difference in beta of up to 10%, which consumes about half of the allowed 20% tolerance in the LHC accelerator if left uncorrected. A rematch of the beam optics using the improved model will be used in all HL-LHC luminosity optics to overcome this problem.

OPTICS TOLERANCES

The small beta functions that are foreseen at the interaction points of the HL-LHC optics lead inevitably to large values of these parameters at the triplet quadrupole lenses. With a maximum of $\hat{\beta} \approx 22$ km the resulting beam size as well as the sensitivity of the beam with respect to external tolerances is considerably increased compared to the LHC standard optics [7]. For each quadrupole magnet in the triplet and matching section the tolerances have been determined, keeping the overall budget of the resulting beta beat within the limit that has been defined for the LHC, $\Delta\beta/\beta \leq 20\%$. The values obtained are summarised in Fig. 6 for the most critical case of the triplet magnets and will act as input for the power converter and magnet design.

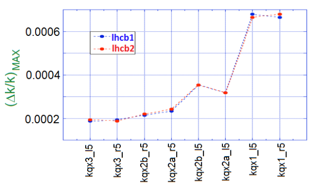

Figure 6: Tolerances for the triplet gradient accuracy.

LOW LUMINOSITY IRS

One of the main features of the ATS [2] is the telescopic squeeze, as shown in Fig 1: While the strengths of the matching quadrupoles in the high luminosity regions IR1 and 5 are limited, the adjacent LHC sectors are used to reach the goal of smallest β* values: e.g. The matching quadrupoles in IR2 and IR8 are used to create a beta beat wave that leads to β*=15 cm in IP1, while the structure remains achromatic due to the increased values of β at the location of the sextupoles. The beam optics at the experiments located in IR2 and IR8 have been re-optimised according to the latest β* values requested by the Alice and LHCb collaborations, while being still compatible with the ATS squeeze of IR1 and 5. Fig 7 shows an example for the resulting beam optics in IR 2 and IR8. The Twiss functions had to be matched on one side to the standard periodic FODO structure of the arc, on the opposite side it had to create the beta wave, needed for enhanced luminosity in IP1. For the complete set of beam optics foreseen, in accordance to the desiderata of the experiments, a matched solution could be established, keeping the overall phase advance over the corresponding section unchanged [8].

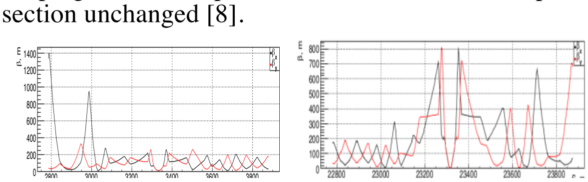

Figure 7: Beam optics of IR2 at β* =10 m and of IR8 at β*=3 m in ATS mode to squeeze IR1 down to 15cm.

OPTICS TRANSITIONS

Special care has been taken to study the beam optics during the beta-squeeze procedure. In several steps the beam optics has been transferred from the new LHC injection optics to the so-called pre-squeeze optics that results in a beta value at the IPs of β*=44cm. Solutions for the optics transition have to meet a number of constraints concerning the phase advance, the tolerable beta beat and the boundary conditions from the magnet technology. At any moment a smooth transition is required for the quadrupole strengths. Step-like change in the normalized gradients, zero crossings of the gradients or situations that lead to intolerable hysteresis and saturation have to be avoided. A successful scenario has been developed fulfilling all these requirements. As an example a part of the resulting gradient functions are plotted in Fig 8. The complete study is summarised in [9].

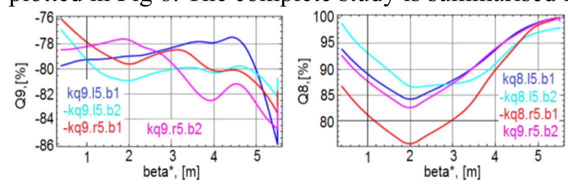

Figure 8: Smooth gradient changes optimised for optics transition between injection and pre-squeeze optics.

ALTERNATIVE APROACHES

Alternative concepts have been studied in parallel to the ATS baseline to explore the parameter space of the LHC lattice. They include lattice modifications like a new layout of the matching section, replacing Q5 and Q6 by a doublet, reinforcing Q7 by a longer quadrupole and replacing Q4 by a quadrupole triplet. Considerably higher lattice flexibility has been reached and a lower attainable beta function at the IP [10]. Figure 5 shows a possible solution. Based on a standard mini beta scheme in the LHC insertions LSS1 and LSS5, a value of β^*=15 cm has been obtained. While the momentum acceptance for these options is still under study, the experience gained may offer alternative ways to reach HL-LHC target β* without the ATS mechanism.

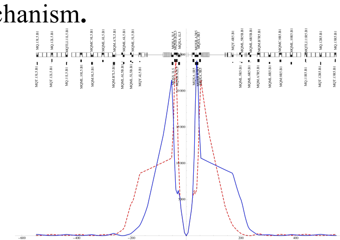

Figure 9: Proposed alternative scenario and lattice modification to reach the required β* values.

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