OPTICS TRANSITION BETWEEN INJECTION AND COLLISION OPTICS FOR THE HL-LHC UPGRADE PROJECT*

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Abstract

Plans for the luminosity upgrade of the LHC collider at CERN (HL-LHC) are based on implementation of magnets with larger apertures in the interaction regions, together with the ATS [1] technique to reach very low values of the beta function at the collision points. Aperture restrictions mean that the collision optics can only be applied after ramping to high energy. The transition from injection to collision optics will be carried out in two stages, and will involve varying the strengths of the quadrupoles within the straight sections. Solutions for the optics transition have to meet a variety of challenging constraints, including constraints on the phase advances and Twiss parameters throughout the straights involved in the transition, specified minimum and maximum strengths of the quadrupoles, etc. Moreover, to minimise the time taken for the transition and to simplify the overall process, the variation of the quadrupole strengths should be as smooth as possible, especially for the strongest quadrupoles. Avoiding changes of slope as much as possible will also minimize hysteresis effects in the super-conducting matching quadrupoles involved in the process. This paper presents one possible solution for the optics transition, calculated for the HLLHCv1.0 [2] version of the optics and layout of the HL-LHC.

INTRODUCTION

The current optics and layout version HLLHCV1.0 [2] proposed for the luminosity upgrade project HL-LHC [3] will reach the lowest values of the beta function at the interaction points for IR1 (ATLAS) and IR5 (CMS) using the Achromatic Telescopic Squeeze (ATS) scheme. To take advantage of this scheme, these IRs will be equipped with new Nb3Sn super-conducting quadrupoles in the inner triplet, with aperture 150 mm and field gradient 140 T/m

In operation, the optics in HL-LHC will remain unchanged from injection at 450 GeV through the energy ramp to 7 TeV. Then at this energy, a transition from injection to collision optics will be performed in two stages. First, there is a 'pre-squeeze', in which the beta functions at the interaction points are reduced by adjusting the quadrupole strengths within each respective interaction region (IR), including additional phase matching constraints (w.r.t. a standard squeeze) in the case of IR1 and IR5 (see later). In particular, the values of β^* in IR1 and IR5 are reduced from 6 m to 44 cm; and β^* in IR8 is reduced from 10 m to 3 m while β^* stays to 10 m at IP2. In the second stage, the telescopic part of the ATS scheme is applied: reductions in β^* from 44 cm to 15 cm in IR1 and IR5 are achieved by adjusting the quadrupole strengths in the neighbouring straight sections (i.e. IR2 and IR8 for IR1, and IR4 and IR6 for IR5). There is no variation of quadrupole strengths in the low-beta insertions IR1 and IR5 during this stage.

The insertions IR1 and IR5 have identical hardware layout and optics, except in respect of the crossing-angle scheme. In the following, we will consider the transition only in IR5. An identical transition can be assumed for IR1.

IR5 MATCHING CONDITIONS

The left and right side of IR5 includes 13 superconducting quadrupoles that are placed symmetrically with respect to the IP. The inner triplet assembly consists of three quadrupoles (Q1, Q2 and Q3) in which Beam 1 and Beam 2 share the same vacuum chamber. On both sides of IR5, each unipolar double-bore quadrupole (from Q4 to Q10, inclusive) has its own power converter that allows the field gradient in the two apertures (i.e for Beam 1 and Beam 2) to differ by up to 50 % (30 % recommended), depending on the quadrupole strength. In order to diminish the effects of hysteresis, it is desirable to reduce the field gradient in these quadrupoles by not more than 15 % from their specified field limit. In addition to the main quadrupoles, there are 'trim' quadrupoles (QT11, QT12 and QT13) that have individual bipolar power converters.

A number of matching conditions and constraints must be respected during the optics transition from injection to pre-squeeze. The lattice functions at either end of IR5 must be kept fixed to maintain correct matching with the adjacent sectors. The Twiss alpha functions $\alpha_{x,y}$ and the dispersion D_x and D'_x should be kept at zero at the IP throughout the transition. There are also constraints on the minimum and maximum strengths of the quadrupoles involved in the transition. Finally, there are specified values for the phase advances over the left and right sides of IR5.

During the first step of the transition, β^* is maintained at a constant value of 6 m and the inner triplet quadrupoles have fixed strengths; however, the total (horizontal/vertical) phase advances over IR5 are adjusted to the values specified for the ATS pre-squeeze optics. Then, keeping the to-

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tal phase advance constant, a linear change of the left and right parts is carried out with a reduction of β^* from 6 m to 3.4 m. This step involves all quadrupoles in the IR. In the final step, a further reduction of β^* to 0.44 m is performed at fixed matching conditions imposed on the phase advances over the left and right side of the IR.

The pre-squeeze optics with $\beta^* = 3.4$ m is predefined; this paper describes the transition to reduce the β^* from 6 m to 0.44 m, prior to application of the telescopic part of the squeeze.

IR5 OPTICS TRANSITION

Since the values of the quadrupole strengths at the injection with $\beta^* = 6$ m and ATS pre-squeeze optics with $\beta^* = 3.4$ m and $\beta^* = 0.44$ m are known, a first approximation to the optics transition can be calculated as a linear interpolation of the field gradient in each quadrupole taken between the three given values of β^*. This solution does not meet the required matching conditions at β^* other than the given values. However, we use it as a starting point for a set of optimisations in MADX. Each optimisation is designed to satisfy the conditions on the optics at a different value of β^*, in small steps from 6 m to 0.44 m.

The matched solution for each value of β^* may differ significantly from the initial estimate (obtained by linear interpolation). Applying a moving average to the matched solution, the mean strength for each quadrupole (over a range of values of β^*) is calculated; and a new transition is obtained by making a linear interpolation between the mean quadrupole strengths at a number of different values of β^*. Using this interpolation as a new starting point, the optimisation in MADX is performed again, to find a new solution satisfying the optics constraints.

This procedure must be iterated several times to achieve smooth and continuous curves of quadrupole strength as a function of β^*, which exactly satisfy the required matching conditions in the range of β^* from 6 m to 0.44 m. In order to achieve more rapid convergence, it is useful to exclude some of the trim quadrupoles from the first few iterations, so that their strengths evolve over the transition according the initial linear interpolation. The same approach can be applied to the triplet for some intermediate iterations in the procedure. All quadrupoles are involved in the final iterations.

Given the number and variety of constraints, it is difficult to find an ideal solution for the transition, in which the quadrupole strengths change monotonically.

A few solutions of the optics transition in IR5 have been found using the strategy described above. Figure 1 shows one particular solution for the optics transition (referred to as IR15.T.v3) that meets all required matching constraints and conditions. This particular transition is obtained from 8 iterations with 2 cm steps in β^*. The phase advances over the left and right sides of IR5 evolve with β^* as shown in the top-left plot on Fig. 1.

The vertical axes on the plots (except top-left plot) give

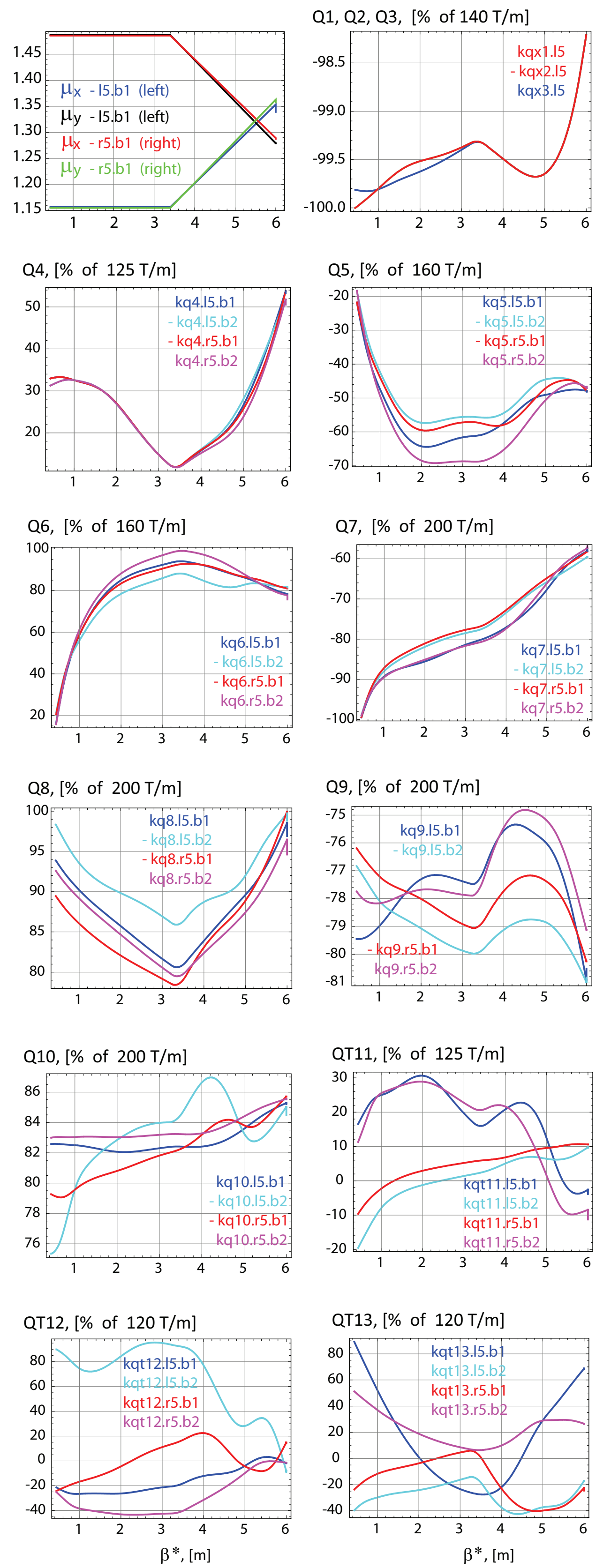

Figure 1: Variation of field gradient in IR5 quadrupoles during transition from injection to 'pre-squeeze' optics. Phase advances over the left and right sides of IR5 are shown on the top-left plot.

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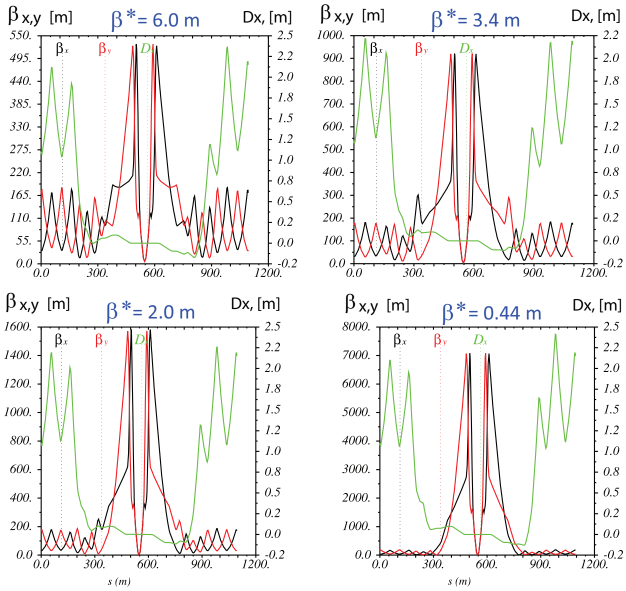

Figure 2: IR5 optics snapshots during the transition.

the strength of each quadrupole as a percentage of the maximum field. Horizontal axis on all plots give the value of β^*. Variation of field gradient in the quadrupoles located on the left side of the IR correspond to the blue (for Beam 1) and light-blue (for Beam 2) lines. The red and pink lines show the variation of field gradient for Beam 1 and 2 (respectively) in the quadrupoles located on the right side of the IR.

The quadrupoles in the triplet have identical field variation from $\beta^* = 6$ m down to 3.4 m, and then split between Q1/Q2 and Q3. An additional symmetry constraint is imposed on the left and right Q4 quadrupoles to maintain identical field variation in its respective apertures for Beam 1 and Beam 2 in the range of β^* from 0.44 m to 3.4 m. The solution converges to the predefined pre-squeeze optics with $\beta^* = 3.4$ m where the Q4 has low gradient. Field variation in other quadrupoles takes place outside the low-field domain.

As showed in Fig. 2, sticking to the optimal ATS phase advances up to a too large β^* (up to $\beta^* = 3.4$ m, presently) is non-natural for the LHC low-beta IRs which were not designed for these additional matching constraints (see peak beta at Q6 rising up from $\beta^* = 44$ cm to 3.4 m). This made the connection up to the injection optics rather "acrobatic", which is clearly illustrated in Fig. 1 by the change of slope of the IT gradients.

BETA-BEATING

To minimize the time taken for the transition, and to simplify the overall process and control, the transition should to be done with linear change of field gradient between a number of points taken with some step of β^*. In this case, beta-beating of some magnitude will result. The amplitude of the beta-beating depends on the size of the step, and

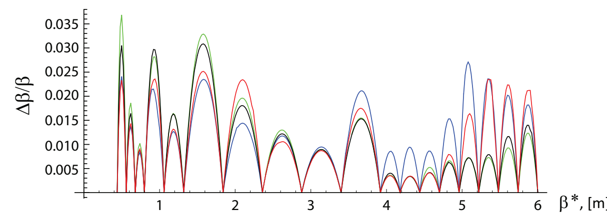

Figure 3: Beta-beating calculated from linear interpolation of the optics transition in the IR5 and IR1, taken with non-uniform step in β^*. The black, red, green and blue lines correspond to the maximum beta-beating of β_x, β_y for Beam 1 and β_x, β_y for Beam 2, respectively.

the deviation of interpolated results from the matched solution. Beta-beating larger than 5% might not be acceptable while a transition with a small step in β^* could take a long time. The maximum beta-beating can be kept below 3.7% by making linear interpolations of the optics transition as follows: steps of 26 cm from $\beta^* = 6$ m to $\beta^* = 3.92$ m; steps of 52 cm from $\beta^* = 3.92$ m to $\beta^* = 1.32$ m; steps of 26 cm from $\beta^* = 1.32$ m to $\beta^* = 0.8$ m; steps of 12 cm from $\beta^* = 0.8$ m to $\beta^* = 0.44$ m. The resulting maximum beta-beat that occurs under this scheme is shown in Fig. 3.

FINAL REMARKS

Solutions for the optics transition in IR5 and IR1 that meet all required matching constraints and provides ATS pre-squeeze optics in the range of β^* from 3.4 m to 0.44 m has been found. In most quadrupoles, hysteresis effects should not be strong, since any changes of slope (of field gradient as a function of β^*) take place far from the low-field domain. However, in some cases the trim quadrupoles have a change in slope near zero field. Relaxing the constraints that impose convergence to the predefined optics with β^* of 3.4 m can allow smoother solutions because of the greater flexibility that this provides. After discussions with experts in magnet modelling it became clear that proposed solution for the optics transition meets operational requirements of the quadrupoles, and can be technically implemented.

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