LAYOUT AND OPTICS SOLUTION FOR THE LHC INSERTION UPGRADE PHASE I

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Abstract

The main guidelines of the LHC IR upgrade Phase I project are the development of wider aperture (120 mm) and lower gradient (120 T/m) quadrupoles using the well-characterized Nb-Ti technology in order to build new inner triplets (IT) for the ATLAS and CMS experimental insertions, while minimizing the hardware modifications in the other parts of these insertions, in particular leaving unchanged the so-called "matching section" (MS) and "dispersion suppressor" (DS). While one of the initial goal was to squeeze the optics down to a β^* of 25 cm, optics solutions with a β^* of 30 cm are already at the edge of feasibility, both in terms of the IT and MS mechanical acceptance, gradients of the MS and DS quadrupole magnets, and correctability by the arc sextupoles of the huge chromatic aberrations generated at low β^*. The layout of the new inner triplet and the corresponding injection and collision optics will be presented and analyzed in terms of aperture and chromatic correction.

INTRODUCTION AND MOTIVATION

Reducing the beam sizes at the interaction point, that is acting on β^* at constant transverse emittances, is a key ingredient to boost the performance of any collider. Going in this direction, the limitations are two-folds, related to the mechanical acceptance of the inner triplet (IT), but also coming from the rest of machine: chromatic aberrations, possible aperture restrictions in the rest of the low-β insertion, behavior of the matching quadrupoles at low β^*.

Concerning the IT aperture related constraints, it was realized a few years ago that a long and weak enough inner triplet (basically with constant integrated gradient) could always offer more aperture than actually needed by the beam, regardless of β^* and of the technology chosen for the triplet [1, 2]. Using some rough scaling laws, it is indeed easy to see that for a given technology defined by a maximum peak field B_{peak} reached in the magnet coils, and for a given aperture Coil_{ID} specified for the inner triplet (corresponding to an operating gradient $G \propto B_{\mathrm{peak}}/\mathrm{Coil}_{ID}$), the first limitation imposed on β^* is given by [3]:

$$\beta^* \geq \beta^*_{min,IT} \propto \frac{G^{3/2}}{\mathrm{B}^2_{\mathrm{peak}}} \propto \frac{1}{\mathrm{Coil}_{\mathrm{ID}}^{3/2}\,\mathrm{B}_{\mathrm{peak}}^{1/2}}, \qquad (1)$$

which, in principle, can be arbitrarily relaxed assuming a weak and long enough inner triplet of very large aperture.

While of different nature, the optics limitations coming from the non-IT side of the ring can in general be quantified by an upper bound imposed on the peak β-function β_{IT} which is reached in the inner triplet, and then shall be chromatically corrected ($\beta_{IT} \lesssim \beta_{IT}^{max} \approx 11$ km for the present
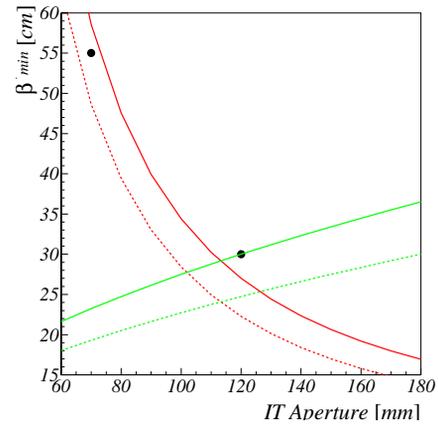
Figure 1: Limits on β^* vs triplet aperture imposed by the current chromatic limit of the LHC (green curves) and by the mechanical acceptance of the inner triplet (red curves) in the case of a Nb-Ti or Nb$_3$-Sn inner triplet (solid and dashed lines, respectively). The two black dots represent the existing LHC triplet (70 mm, $\beta^* = 55$ cm) and the Phase I Nb-Ti triplet (120 mm, $\beta^* = 30$ cm).

chromatic limit of the LHC [3]) and optically matched to the arcs while fulfilling a series of conditions (aperture and strength) given by the other magnets of the low-β insertions ($\beta_{IT} \lesssim \beta_{IT}^{max} \approx 13$ km [3]). A second condition can be therefore derived for the minimum possible β^* [3]:

$$\beta^* \geq \beta^*_{min,Ring} \propto \frac{1}{\beta_{IT}^{max}\sqrt{G}} \propto \frac{\mathrm{Coil}_{\mathrm{ID}}^{1/2}}{\beta_{IT}^{max}\,\mathrm{B}_{\mathrm{peak}}^{1/2}}, \qquad (2)$$

which, contrary to the first one, is less favorable for low-gradient (i.e. large aperture) inner triplet.

A phase diagram linking the minimum possible β^* and the IT aperture can then be drawn accordingly in the case of the LHC upgrade (see Fig. 1) assuming a given technology for the new triplet (Nb-Ti and Nb$_3$-Sn in solid and dashed lines respectively) and combining the two above conditions: red curves giving the limit on β^* imposed by the mechanical acceptance of the new triplet (assuming a full crossing angle of $10\,\sigma$ and a normalised aperture of $n_1 = 7$, see [4] for more details) and green curves related to the present chromatic limit of the LHC ring ($\beta_{IT} \lesssim 11$ km for two insertions squeezed to β^*_{min} and the arc sextupoles not pushed beyond their nominal strength). The crossing point between the red and green curves therefore give the optimal aperture of the new triplet (which is independent on the choice of the IT technology at a given β_{IT}^{max}-limit) and then the minimum possible β^*:

$$\beta^* \geq \beta^*_{min} \propto \frac{1}{\beta_{IT}^{max^{3/4}}\,\mathrm{B}_{\mathrm{peak}}^{1/2}}. \qquad (3)$$

Following the guidelines of the Phase I project (Nb-Ti technology for the new IT, minimal hardware modifications on the non-triplet side of the machine), the aperture of the new triplet was then optimized accordingly: 120 mm which is compatible with an operating gradient of about 120 T/m for the Nb-Ti technology, and leads to a minimum possible β^* of about 30 cm instead of 25 cm as initially targeted.

OPTICS AND LAYOUT
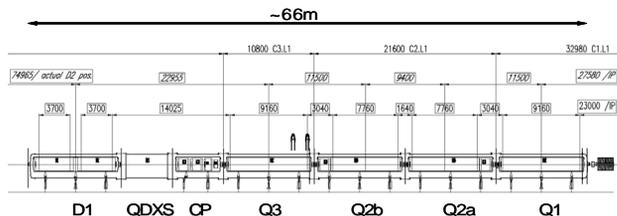
Figure 2: Schematic layout of the new triplet.

As for the current LHC triplet, the layout is based on a symmetric triplet with the same magnetic length for Q1 and Q3 (9.135 m) and a different length for the central quadrupoles Q2a and Q2b (7.735 m). The gradient of Q1 and Q2 is chosen to be 123 T/m and slightly below for Q3 in order to reasonably increase the slope of the β-functions at the triplet exit (Twiss parameter α), which is beneficial for the mechanical acceptance of the matching section without degrading too much the overall matchability of the insertion at low β^*. Orbit correctors are hosted in the Q2a and Q2b cold masses and in a corrector package (CP) located on the non-IP side of Q3. The CP also contains a series of other multipole correctors which are mandatory for the preservation of the dynamic aperture of the machine in collision [5]. The existing warm separation dipoles (D1) installed in the high luminosity insertions IR1 and IR5 do not offer enough aperture for the beam below a β^* of about 50 cm. The proposal for Phase I is based on a superconducting assembly containing two 3.7 m long RHIC DX magnets (180 mm coil aperture). The existing TAS (34 mm ID) will be replaced by a new object with an aperture increased to 50 mm. The aperture of the TAN, or more precisely the separation between the two bores of the existing TAN, is no longer suitable to the new distance between the separation and recombination dipoles D1 and D2. As soon as this distance will be frozen, the cross-section of the new TAN will be specified. Finally, except for new collimation devices installed close to Q5 and possibly additional dipole corrector magnets installed at Q4 which are needed to reach crossing angles above the 0.5 mrad level, the matching section (Q4-Q7) is assumed to be kept unchanged for Phase I.

The corresponding injection ($\beta^* = 14$ m) and collision ($\beta^* = 30$ cm) optics are illustrated in Fig. 3. The full crossing angle is chosen to be $410\,\mu$rad in both cases (see Tab. 1), corresponding to a normalised beam-beam separation more than sufficient at injection and of exactly 10σ in collision. Should this separation be insufficient in collision,

Table 1: Main optics parameters for the new low-β insertions of the LHC.

Parameters	Injection	Collision	Back-up
Energy [GeV]	450	7000	7000
β^* [m]	**14.00**	**0.30**	**0.40**
β_{IT}^{max} [km]	0.3	10.8	8.1
Full X-angle [μrad]	410	410	560
Full parallel sep. [mm]	5.0	1.5	1.5
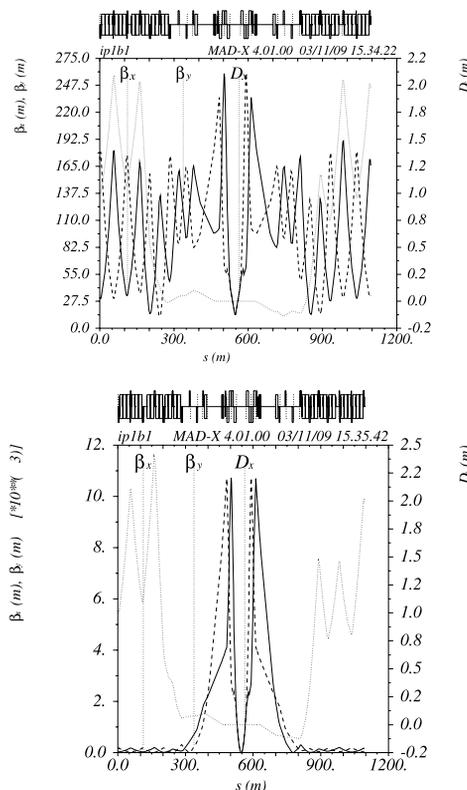
Figure 3: Injection (top) and collision (bottom) optics for the new low-β insertions of the LHC.

a back-up collision optics with a relaxed β^* of 40 cm and a crossing angle pushed up to $\sim 16\sigma$ (560 μrad) is fully compatible with the mechanical aperture of the new IT and will eliminate any potential intensity limitations related to the long-range beam-beam interactions [6].

As previously mentioned, the control of the mechanical aperture in the inner triplet but also in the matching section is of paramount importance at low β^*. The latter is calculated in 2D and is generally expressed in terms of n_1 which characterizes the maximum normalised extension of the primary halo such that the secondary halo is tangential to the cold aperture of the magnets. The target is $n_1 = 7$ taking into account a certain budget for the linear optics imperfections (see [4] for more details). As showed in Fig. 4, the new triplet has a normalised aperture of about $n_1 \approx 7.5$ at $\beta^* = 30$ cm. With the exception of the existing TAN, the aperture in the matching section is still comfortable (while substantially reduced compared to the nominal
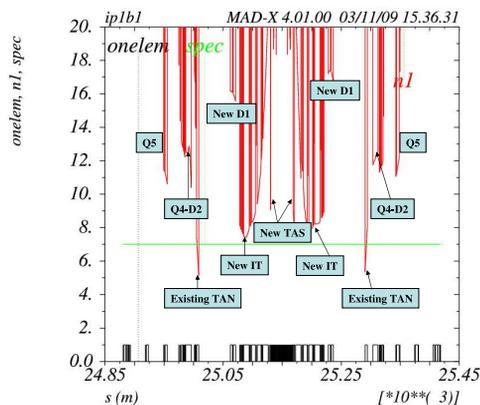
Figure 4: Aperture plot of the new insertion in collision.

Figure 5: Chromatic variations of the betatron tunes (left) and envelop of the off-momentum β-beating wave $\partial_\delta \beta/\beta$ along the machine starting from IP3 (right), before (top) and after (bottom) chromatic correction at $\beta^* = 30$ cm.

collision optics of the LHC with $\beta^* = 55$ cm) thanks to a fine tuning of the triplet layout and of the Q3 gradient which maximizes the negative slope of the β-functions at the triplet exit (see [3] for more details). The price to pay however is to push some IR matching quadrupoles close to the limit, either operating at rather low gradients (case of Q5 and Q6) or near to their nominal strength (case of Q7).

CHROMATIC CORRECTION

As described in details in [7] and summarized below, an overall modification of the LHC optics is needed in order to warrant the correctability of the huge chromatic aberrations induced by the inner triplet at low β^*, that is not only its additional contribution to the linear chromaticity of the ring but also its impact on the non-linear chromaticity Q'' and Q''' and on the off-momentum β-beating. In this respect, specific phasing conditions shall be fulfilled from mid-arc to mid-arc and on the left and right sides of the low-β insertions. Under these conditions, the lattice sextupoles belonging to the two consecutive sectors located on either side of each low-β insertion need to be pushed to nominal strength in order perform the chromatic correction of one single triplet at $\beta^* = 30$ cm. Since the LHC contains 8 sectors, this clearly defines the current chromatic limit of the machine: $\beta_{IT}^{max} \lesssim 11$ km corresponding to $\beta^* \geq 30$ cm in the case case of two low-β insertions equipped with Nb-Ti inner triplets. The benefits of the correction is illustrated in Fig. 5 showing the chromatic variations of the betatron tunes and the evolution of the off-momentum β-beating envelop along the ring at $\beta^* = 30$ cm. After correction, the second and third order chromaticity are almost perfectly corrected and the chromatic variations of the tunes are given by the linear chromaticity (matched to 2 units in this case). The off-momentum β-beating is nicely vanishing in the inner triplets of IR1 and IR5, which is found to have a beneficial impact on the dynamic aperture of the machine [5], and in the collimation insertions IR3 and IR7, which warrants a preservation of the hierarchy between the different collimation and protection devices of the ring.
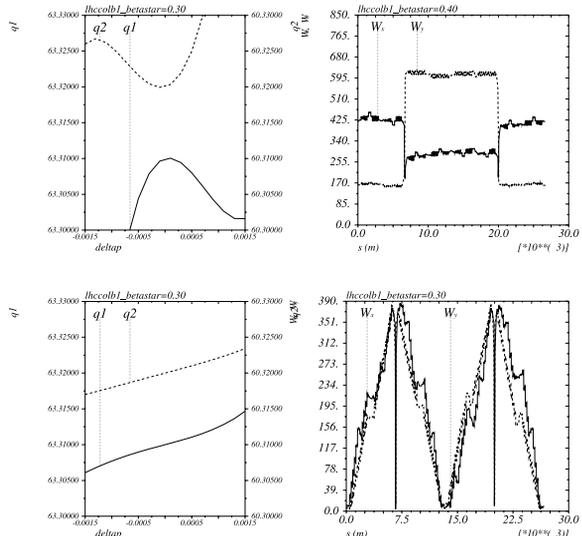
CONCLUSIONS

For a given triplet technology, the minimum possible β^* is serverely constrained by several optics limitations imposed by the non-triplet side of the LHC ring, in particular by its current chromatic correction system. A β^* of 30 cm is nevertheless reachable in the ATLAS and CMS experiments assuming new Nb-Ti triplets are installed with an aperture of 120 mm and an operating gradient of about 120 T/m. Under these conditions, however, several magnet circuits shall be pushed to the limits, which is the case for defocusing sextupole families of the LHC arcs and some matching quadrupoles of the new insertions either operating at low gradient or near to their maximum strength.

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