Optics Challenges and Solutions for the LHC Insertion Upgrade Phase I

Stéphane Fartoukh, CERN, Geneva, Switzerland

Abstract

The goal of the LHC Insertion (IR) Upgrade Phase-I is to enable a reliable operation of the machine with a performance at least doubled with respect to its design luminosity. One key ingredient is ideally a reduction of β^* down to 25 cm, using a new inner triplet (IT) with longer Nb-Ti quadrupoles operating at a lower gradient ($\sim$ 120 T/m) and therefore offering a larger aperture (120 mm). Reducing β^*, but also operating at a lower IT gradient (which, at a given β^*, further increases the size of the β-functions all over the long straight section), has however a certain number of drawbacks which cannot be solved by only increasing the aperture of the new low-β quadrupoles. Without modifying the current layout of the matching section (MS) and assuming that the arc sextupoles cannot safely operate above nominal current (550A), optics solutions with a β^* of 30 cm are already at the edge of feasibility, both in terms of mechanical aperture in the MS and new IT (assuming 120 mm aperture), in terms of gradients for some MS and DS quadrupoles and in terms of chromatic correction. These limitations will be analyzed in detail, in particular concerning the chromatic correction of the new inner triplet which requires a global modification of the present LHC optics. Concerning the high luminosity insertions, the layout of the new IT and the corresponding injection and collision optics (with $\beta^* \geq 30$ cm) will be presented and studied in detail both in terms of mechanical aperture, chromatic correction, squeeze-ability, dynamic aperture and beam-beam effects.

FACTS AND NUMBERS

Triplet aperture

Reducing the beam sizes at the interaction point, that is acting on β^* at constant transverse beam emittances, is a key ingredient to boost the performance of any collider. The first limit reached in this case is related to the available aperture of the inner triplet (IT) where the horizontal and vertical peak β-functions, namely β_{IT}^{max}, vary approximately as follows with β^* and with the operational gradient G of the low-β quadrupoles:

$$\beta_{IT}^{max} \propto \frac{1}{\beta^* \sqrt{G}} \,. \tag{1}$$

About five years ago, the LHC Upgrade community starts then to realize that long enough quadrupoles with a weaker gradient (that is at more or less constant integrated gradient) could always offer more aperture than actually needed by the beam, regardless of the choice of β^*, of the layout of the interaction region and of the technology chosen for the inner triplet [1]. This observation was based on the two following facts.

- For a given technology, the inner diameter (ID) of the coils and the operating gradient are roughly constrained by the following scaling law:

$$\mathrm{Coil_{ID}} \propto \frac{\mathrm{B_{peak}}}{G} \,, \tag{2}$$

  with $\mathrm{B_{peak}}$ being the peak magnetic field reached in the quadrupole coils (typically 80-85% of the short sample limit). Then, one can empirically observe that, in the LHC, the inner dimension of the beam-screen (if any) scales almost linearly with the coil aperture:

$$\mathrm{BS_{ID}} \sim 83\% \times \mathrm{Coil_{ID}} \propto \frac{\mathrm{B_{peak}}}{G} \,. \tag{3}$$

- Assuming a given β^* and an operating gradient G for the inner triplet, the beam requirement in terms of available IT aperture can be estimated based on the peak β-function reached in the inner triplet β_{IT}^{max}, with of course some preliminary assumptions concerning the minimum crossing angle needed to separate the beams after the collision (e.g. $\theta_c = 10\sigma$) and the extension of the secondary halo in units of σ (e.g. $8.5\,\sigma$ corresponding to a so-called normalised aperture of $n_1 = 7$ [2] in the triplet) :

$$\mathrm{Beam_{OD}} \propto \sqrt{\epsilon \beta_{IT}^{max}} \overset{\text{Eq. 1}}{\propto} \frac{\sqrt{\epsilon}}{\sqrt{\beta^*}} \times \frac{1}{G^{1/4}} \,, \tag{4}$$

  with ϵ the transverse physical emittance of the beam at the design energy of the machine. It is worth mentioning that the above scaling law remains approximative within let say 10%. This is due to the fact that specific contributions to the beam aperture budget are either constant with β_{IT}^{max}, as the budget reserved for the closed orbit, or vary more rapidly with the increase of β_{IT}^{max} such as the contribution of the spurious dispersion induced by the crossing angle in one high luminosity insertion and then exported to the other insertion ($\propto \theta_c\,[\sigma] \times (\beta_{IT}^{max})^{3/2}$).

Combining the scaling laws (3) and (4), it was then concluded that, to some extent, β^* could be chosen as a free parameter for the design of the new inner triplet and could even be minimized going in the direction of decreasing the operational gradient of the new IT:

$$\mathrm{Beam_{OD}} \leq \mathrm{BS_{ID}} \rightarrow \beta^* \geq \beta^*_{min} \equiv \epsilon\lambda_1 \times \frac{G^{3/2}}{\mathrm{B^2_{peak}}} \,, \tag{5}$$

where the coefficient λ_1 only depends on the operational margins injected into the design goal, that is typically a

normalised aperture n_1 and a crossing angle θ_c equivalent or larger than the ones chosen for the nominal LHC.
Based on this observation, a first upgrade of the LHC could therefore be envisaged (see e.g. [3] and [4] for the latest proposals) counting on a substantial decrease of β^* while still keeping the Nb-Ti technology for a new inner triplet.

One of the two proposals [3] consisted in the exchange of the existing LHC inner triplet by about 10 m long Nb-Ti quadrupoles, operating at a gradient of 120 T/m with a coil aperture of 130 mm corresponding to an effective clearance of about 120 mm for the beam (beam-screen inner dimensions). Such an inner triplet aimed to be compatible with a β^* as low as 25 cm at nominal emittance, corresponding to a peak β-function β_{IT}^{max} of about 13 km, while still offering a very substantial aperture margin of about 6σ (3σ per beam) for collimation. At posteriori, a beam clearance of 120 mm was however found to be quite optimistic by about 20 mm[1] with respect to the performance of Nb-Ti quadrupoles at an operating gradient of 120 T/m.

The second proposal [4] envisaged even longer and weaker Nb-Ti quadrupoles with coil aperture as large as 190 mm, therefore eliminating any potential aperture restrictions in the inner triplet (at least down to a β^* of 25 cm) while still offering huge margins, either for collimation, for operating the machine with a crossing angle larger than 10σ or, in case of need, for shielding the IT against the debris coming from the IP at large peak luminosity.

Optics limitations coming from the rest of the ring

However, the two above proposals were ruled out by hard limits coming from the rest of the machine [7], either not yet identified at the time of the project approval, as the severe aperture restrictions in the matching section at low β^* [5], or known but only solved a posteriori, as the huge chromatic aberrations induced by the inner triplet when the optics is squeezed [6]. As we will see later on, these two limits can be nicely quantified by a single constraint imposed on the maximum acceptable peak β-function, namely β_{Ring}^{max}, reached in the inner triplet. This limit amounts to about 11-12km in the existing nominal machine, assuming no modification of the matching section and supposing that the lattice sextupoles cannot safely operate above the nominal current of 550A:

$$\beta_{IT}^{max} \leq \beta_{Ring}^{max} \sim 11 - 12\text{km}\,. \tag{6}$$

This limit is already a factor of 2.5 higher than the peak β function actually reached in the existing inner triplet, operating at a gradient of 205 T/m with a β^* of 55 cm. Nevertheless this limit imposed by the ring is still below a peak β-function of 13km which, as mentioned above, would correspond to $\beta^* = 25$ cm and a triplet gradient of 120 T/m.
Coming back to Eq. 1, such a limitation clearly imposes a severe limitation on the minimum possible β^*:

$$\beta_{IT}^{max} \leq \beta_{Ring}^{max} \rightarrow \beta^* \geq \beta_{min}^* \equiv \frac{\lambda_2}{\beta_{Ring}^{max}\sqrt{G}}\,, \tag{7}$$

where the proportionality coefficient λ_2 depends only very moderately on the triplet layout [2]. This coefficient may vary or not with the physical emittance of the beam depending on whether the β_{Ring}^{max} limit is induced by aperture restrictions or by strength limitations in the magnets located on the non-triplet side of the machine. Finally, it is generally recommended to tune carefully the λ_2 coefficient, in practice increase it by let say 20%, such that the corresponding collision optics does not exceed a certain fraction of the β_{Ring}^{max} limit (ideally 80%) in order to preserve some flexibility in terms of optics adjustment or chromatic correction. This being said, contrary to the condition (5), the relation (7) imposes an increase of the minimum β^* when decreasing the operating gradient G of the inner triplet.

Optimum IT parameters and min. possible β^*

Combining the conditions (5) and (7) imposed by the inner triplet on one side and by the rest of the machine on the other side, it is then clear that the minimum possible β^* can no longer be chosen as a free parameter to design the new inner triplet. More precisely an optimum gradient (corresponding to given coil aperture at a given technology) can be fully determined in order to minimize β_{min}^*:

$$\begin{cases} G \equiv \sqrt{\dfrac{\lambda_2}{\lambda_1 \epsilon}} \times \dfrac{\mathrm{B_{peak}}}{\sqrt{\beta_{Ring}^{max}}} \rightarrow \mathrm{Coil_{ID}} \propto \dfrac{\mathrm{B_{peak}}}{G} \propto \sqrt{\epsilon \beta_{Ring}^{max}} \\ \beta_{min}^* = \lambda_1^{1/4} \lambda_2^{3/4} \times \dfrac{\epsilon^{1/4}}{\left(\beta_{Ring}^{max}\right)^{3/4} \sqrt{\mathrm{B_{peak}}}}\,. \end{cases} \tag{8}$$

This last relation deserves a very special attention. Without even talking about operational margins (implicitly included in the proportionality coefficients $\lambda_{1,2}$ here above), both the triplet technology and the limitations coming from the rest of the machine (quantified by $\mathrm{B_{peak}}$ and β_{Ring}^{max}, respectively, in Eq. 8) play a very similar role in the minimization process of β^*. However none of these ingredients are actually included in the scope of the Phase-I upgrade project. As a result, in order to still obtain a decent reduction on β^*, there was no other solution than giving up the second main motivation of the Phase-I project, which was to guaranty a substantial aperture margin in the new inner triplet. De facto, it was then decided to base the design of the new triplet onto the current LHC standards in terms of normalised aperture ($n_1 \sim 7$) and full crossing angle ($\theta_c \sim 10\sigma$). It was also assumed that no specific margins were needed in terms of peak β-functions

[1] out of which 10 mm comes from the fact that, in practice, both the thickness and the mechanical tolerances of the cold bore and the beam-screen are found to scale linearly with the coil aperture (see Eq. 3).

[2] As an example, at constant peak β-function in the inner triplet, and assuming that the distance between Q2a and Q2b has been minimized as much as possible, β^* can only be reduced by about 7% and then by hardly more than 10% assuming two or three different lengths for the Q1, Q2 and Q3 inner triplet quadrupoles, compared to a situation where all low-β quadrupoles would have exactly the same magnetic length.

reached in the inner triplet in comparison with the hard limit of $\beta^{max}_{Ring} \sim 11 - 12$ km given by the rest of the machine. Under these conditions the minimum possible β^* is found to be around $\beta^*_{min} = 30$ cm corresponding to a peak β-function of about $\beta^{IT}_{max} \sim 11$ km reached in the new triplet. This minimum β^* can actually be met assuming an operating gradient of about $G = 120$ T/m for the new triplet which is compatible with a coil aperture of $\mathrm{Coil_{ID}} = 120$ mm for the Nb-Ti technology, that is a beam clearance estimated to about 100 mm for the inner dimension of the new beam-screen [8].
Should we have used the same assumptions as the ones of Ref. [3] (i.e. only 10 mm aperture needed to accommodate the cold bore and beam-screen, optimistic Nb-Ti performance by about 10% at a given coil aperture), the same analysis would have concluded to a 110 mm - 140 T/m triplet corresponding to a minimum possible β^* of about 28 cm, still above the initial target of 25 cm.

Of course both aperture margin and optics flexibility can simultaneously be restored a posteriori operating with a β^* larger than 30 cm, typically at the level of 35-40 cm, but then degrading more or less the peak luminosity of the machine. This will form the subject of the next section, while the second part of the paper will focus on the various optics limitations mentioned here above, envisaging possible cures whenever possible. The last part will then describe in detail the solution proposed for the Phase-I upgrade in terms of layout, optics, correction of the chromatic aberration, strategy for the squeeze, dynamic aperture and beam-beam effects.

EXPECTED PERFORMANCE FOR PHASE-I

One of the key parameters to quantify the performance of a collider is its design peak luminosity. Assuming a gaussian bunch distribution and round beams, the latter is given by the well-known formula

$$\mathcal{L} = \frac{n\, N_b^2\, f_0}{4\pi\epsilon\beta^*} \times \underbrace{\frac{1}{\sqrt{1+\phi_w^2}}}_{\text{geometric luminosity loss factor}} \qquad (9)$$

with n the number of bunches, N_b the number of particles per bunch, f_0 the revolution frequency, ϵ the r.m.s. transverse physical emittance of the beam, β^* the size of the β-function at the interaction point and ϕ_w the so-called Piwinsky angle. This angle depends on β^*, on the r.m.s bunch length σ_z and on the full crossing angle θ_c required to separate the beams after the collision:

$$\phi_w \equiv \frac{\theta_c\,[\sigma] \times \sigma_z\,[\mathrm{m}]}{2\,\beta^*\,[\mathrm{m}]}\,. \qquad (10)$$

These parameters are summarized in Tab. 1 both for the nominal optics and beam parameters of the LHC and for possible scenarios which have been or are currently envisaged for the IR upgrade phase I. Most of the beam parameters (energy, number of bunches, bunch length, transverse emittance) are not expected to change for Phase I. The remaining parameters to boost the machine performance are then the bunch charge and the optics, i.e. the choice of β^* and of the crossing angle.

Parameters	LHC	sLHC Phase I		
Energy [TeV]	7	7		
Number of bunches	2808	2808		
Bunch length [cm]	7.55	7.55		
Normalised emittance [μrad]	3.75	3.75		
β-function at IP [cm]	55	*25*	30	40
Full crossing angle [μrad]	285	*450*	410	560
Piwinsky angle [rad]	0.65	*1.51*	1.26	1.49
Lumi loss factor	0.84	*0.55*	0.62	0.56
Protons / bunch $[10^{11}]$	1.15	*1.70*	**1.70**	**1.70**
Peak lumi $[10^{34}\ \mathrm{cm^{-2}s^{-1}}]$	1.01	*3.19*	**2.99**	**2.01**

Table 1: *Optics and beam parameter list for the nominal LHC and for the sLHC Phase I.*

As shown in Tab. 1, the gain of luminosity becomes rapidly marginal when decreasing β^* below 30 cm, of the order of 6.6% in relative between 30 cm and 25 cm assuming the same bunch charge and the same crossing angle in units of sigma ($\theta_c = 10\,\sigma$ in both cases). Furthermore, as already mentioned and discussed in more detail in the next section, optics solutions with a β^* of 30cm are already at the limit of feasibility with a operating gradient of 120 T/m for the new triplet, due to gradient and aperture limitations in the matching section but also strength limitations in the lattice sextupoles of the arcs in order to warrant a proper compensation of the chromatic aberrations induced by the inner triplet (linear but also non-linear chromaticity and off-momentum β-beating).

Under these conditions, assuming a reliable operation of the machine with the so-called "ultimate LHC beam" (i.e. $N_b = 1.70\,10^{11}$ p/bunch) is then the only route to push the peak luminosity by a decent factor, that is let say by a factor of two. Pushing the beam intensity has certainly several drawbacks, most of them being beyond the scope of this paper except the beam-beam effect which could be mitigated by a better balance between the choice of β^* and that of the the crossing angle. Working in a regime where the available aperture is fully utilized in the inner triplet and in the rest of the insertion, an increase of the crossing angle will obviously further degrade the peak luminosity at constant bunch intensity, both due to the increase of β^* imposed by the preservation of the mechanical acceptance of the insertion, but also due the further increase of the Piwinsky angle. On the other hand, increasing the crossing angle can rapidly mitigate the long-range beam-beam interactions and may therefore contribute to gain faster in peak luminosity by increasing the bunch intensity.
Assuming an optimized orbit correction scheme equipping the new inner triplet [9] and supposing that no additional non-common orbit corrector will be installed in the matching section for the Phase-I upgrade, the maximum possible

crossing angle is found to be of the order of 560 μrad. In this configuration, β^* shall be relaxed to 40 cm in order to preserve the mechanical acceptance of the inner triplet and the matching section. At nominal bunch intensity (i.e. $N_b = 1.15\,10^{11}$ p/bunch), the peak luminosity is slightly below $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. On the other hand, it is exactly doubled at ultimate intensity (see fourth column of Tab. 1), while the crossing angle reaches about 16σ, which should eliminate in practice any intensity limitation coming from the beam-beam effect.

A natural target for the collision optics of the sLHC Phase-I is then a β^* ranging in between 30 cm and 40 cm with a crossing angle as large as possible, chosen in practice in between $410\,\mu$rad and $560\,\mu$rad depending on the normalised aperture of the new triplet at a given β^*. Then, in all cases, an increase of the bunch charge beyond nominal will be necessary in order to gain a factor of at least 2 for the peak luminosity of the machine with respect to its design luminosity of $10^{34}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$.

The next section will discuss in much more detail several optics related limitations imposed on the choice of β^*. A complete solution for the layout and optics of the new insertion will then be presented in the last section, discussing as well first tracking results obtained at injection and in collision, including or not the beam-beam effect, in a moderate or large Piwinsky angle regime as described in Tab. 1 for the two cases $\beta^* = 30$ cm and $\beta^* = 40$ cm.

LIMITATIONS

In this section we have tried to draw an exhaustive list of the various optics or performance related limitations expected for the LHC Insertion Upgrade Phase-I. Whenever possible, specific cures will be suggested.

Aperture of the inner triplet (IT)

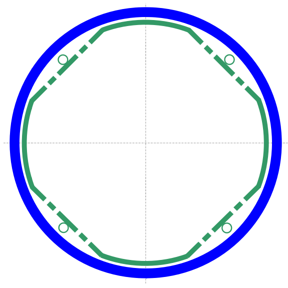


Figure 1: *Schematic cross-section of the new beam screen. Courtesy of N. Kos.*

The coil aperture of the new inner triplet has been chosen to be 120 mm [10], corresponding to an operating gradient of 120 T/m at 80% of the short sample limit [11].

The existing triplet is equipped with horizontally or vertically oriented race-track shape beam-screens. This imposes an hard limitation on the orientation of the beam crossing planes in each of the four experimental insertions of the LHC. The full flexibility will then be restored for the new triplet by choosing a so-called “rounded octagonal” cross-section for the new beam-screens (see Fig. 1). In particular, the new inner triplets will then be equipped with strictly identical beam-screens in the two high luminosity insertions ATLAS and CMS.

More quantitatively, assuming a proper correction of the spurious dispersion produced by the crossing scheme in IR1 and IR5 (see later) and within maximum variations of the order of $\Delta n_1 \sim \pm 0.1$, the normalised aperture of the new inner triplets will no longer depend on the actual orientation of the crossing planes in IR1 and IR5 while, in this case, aperture reductions down to $\Delta n_1 \sim 1$ would be observed with a race-track shape beam-screen [12]. Then, in the standard configuration of a vertical and horizontal crossing scheme in IR1 and IR5, respectively, the normalised aperture of the new triplet is expected to be of the order of $n_1 \sim 7.4$ with a β^* of 30 cm and a crossing angle of 10σ ($410\,\mu$rad). It is worth mentioning that the above estimate assumes the nominal LHC aperture budget [2] for the closed orbit (3mm) and the β-beating (20%), and without any specific correction of the horizontal and vertical spurious dispersion, either coming from the arcs (27% budget in terms of normalised dispersion) or induced by the crossing angles in IR1 and IR5. For any other configurations in terms of polarity or orientation of the crossing scheme (e.g. $\pm 90°$ in IR1 and IR5 which is found to be the worst configuration), the normalised aperture of the new triplet remains above $n_{1,min} = 6.8$ [12].

At this stage two specific measures of different nature can be envisaged to restore a more or less substantial aperture margin in the new triplet at $\beta^* = 30$ cm.

Ordering the beam-screen and cold bore production. The new beam-screen offers a beam clearance estimated to 99.2 mm in the horizontal and vertical planes. This clearance is reduced to 88.8 mm at 45 degrees in order to leave enough room for the four cooling tubes which will equip the new beam-screens [8]. The loss of beam clearance w.r.t. to the coil aperture is therefore quite substantial, approximately 20 mm compared to $\sim$ 10 mm in the existing triplets. This is due to the fact that, for mechanical reasons, the cold bore and beam-screen thickness shall be more or less doubled, but also and mainly due to a linear increase of the manufacturing tolerances of these two objects. Without going to much into the details, an appropriate step could be to produce and measure the cold bore first before fixing the final outer dimension of the beam-screen. In this case an aperture gain ranging in between 2.5 mm and 5 mm could be obtained depending on where the inner diameter of the new cold bore will actually range inside its ± 1.2 mm tolerance band [13]. At a β^* of 30 cm ($\beta_{IT}^{max} \sim 11$ km), this would correspond to an increase of the beam clearance by up to 2σ to be used for collimation (1σ margin per beam) or for pushing the crossing angle up to 12σ in order to mitigate the long range beam-beam interactions. This strategy is of course not excluded but, strictly speaking, not yet inserted in the baseline of the Phase-I project.

Correcting the spurious dispersion. There are two possible sources of spurious dispersion. The first one is created in the LHC arcs mainly due to random a_2 and b_2 errors in the LHC main dipoles and quadrupoles. Its contribution to the aperture of the inner triplet therefore increases moderately when reducing β^* ($\propto 1/\sqrt{\beta^*}$). At least in the vertical plane, there is no mean foreseen for its correction. The second source is the dispersion induced by the crossing scheme in one of the two high luminosity insertions and then propagating to the other insertion. The magnitude of this dispersion wave increases rather rapidly when decreasing β^* (($\propto 1/{\beta^*}^{3/2}$), possibly reaching 4-5 m when β^* is squeezed down to 30cm. Considering the nominal minimum momentum window of $\pm 0.86 \times 10^{-3}$ requested for the LHC at flat top energy [2], the spurious dispersion induced by the crossing angle then corresponds to a substantial loss of aperture, up to 4mm per beam (that is $\Delta n_1 \sim 1.3$ at $\beta^* = 30$ cm).
On the other hand, contrary to the first source, this wave of dispersion arrives at the triplet with a well determined betatron phase. Then, thanks to the new overall optics needed for the chromatic correction of the new triplet (see later), a compensation is also theoretically possible both for the horizontal and vertical spurious dispersion induced by the crossing scheme in IR1 and IR5 [6]. This correction assumes however the generation of orbit bumps with maximum amplitude of the order of 4-5 mm in the four LHC sectors located on either side of each of the two high luminosity insertions [3]. This strategy would then impose a squeeze at non constant closed orbit in the LHC arcs and then an operation of the machine with a non zero nominal closed orbit with all the drawbacks this implies in terms of feed-down effects and non-orthogonality of global correction knobs for the tune, the linear coupling, the chromaticity or even the amplitude detuning controlled via the Landau octupoles. It is nevertheless not at all excluded that at some stage the LHC will have reached enough maturity to be operated in such "exotic" conditions at flat top energy.

To summarise a substantial margin could in theory be restored in the new triplet, up to 13 mm in terms of full aperture, that is almost 3 nominal σ's per beam at a β^* of 30 cm. This margin could then eventually be used for

- reestablishing a less stringent budget for the closed orbit and the β-beating when operating the machine with a peak β-function of more than 10 km in the new IT,

- increasing the operational margins of the collimation system, for instance increasing the 1σ retraction between secondary (n_2) and primary (n_1) collimators and, by this mean, reducing as well the impedances of the secondary collimators (working at constant n_1),

- substantially increasing the full crossing angle above the $10\,\sigma$ standard value in order to mitigate the long range beam beam interactions,

- or sacrificing a big fraction if not all this aperture margin to an additional reduction of β^* down to 25 cm, but for a very moderate gain of performance (see Tab. 1). This would assume of course that no other optics limitations would be hit when following this way, which is actually not the case as we will see later on.

However, pending some clarification, discussion and/or dedicated MD's to validate or not the viability of the two possible remedies proposed here above, this potential aperture margin will no longer be taken into account in all the rest of the paper.

Aperture of the matching section (MS)

Possible optics limitations coming from aperture restrictions in the matching section [5] were discussed rather late during the feasibility study of the Phase-I upgrade and ruled out all the proposals made in the early stage of the project [7].
Before entering into the discussion, it is worth reminding that the existing low β-insertions of the LHC have been fully validated in terms of quadrupole strength and aperture for a β^* down to 25 cm, that is corresponding to a peak β-functions β_{IT}^{max} of the order of 10 km for the 205 T/m operating gradient of the existing triplet. These checks were however performed at a time where it was still not clear whether beam-screens would equip or not the magnets of the long straight section.
For the new triplet ($G \sim 120$ T/m), a β^* of 25 cm would correspond to peak β-functions of the order of 13 km, together with orbit excursions of the order of 12-13 mm due to the crossing angle, therefore almost doubled compared to the nominal LHC. Then the matching section quadrupoles (Q4, Q5 and Q6) and the D2 separation dipole are actually equipped with race-track shape beam-screens. Finally, due to the fact that the mechanical acceptance of the matching section is still very comfortable ($n_1 \gtrsim 12-14$) for the nominal collision optics of the LHC (see Fig. 2), the orientation of the beam-screens in the MS magnets were only optimized based on aperture constraints at injection (H or V oriented beam-screens depending on the polarity of Q5 and Q6) or not optimized at all when it was not strictly needed (natural dipole-like H orientation for the beam-screens equipping all Q4's and D2's) [14]. It is therefore not at all surprising that the mechanical acceptance of the matching section will impose severe limitations below a certain β^* or, more precisely, above a certain β_{IT}^{max}.

At this stage, it is relevant to introduce the so-called cofocal length or parameter P of the inner triplet which, in a given plane, is defined as follows

$$P_{x,y} \equiv \frac{\alpha_{x,y}^{out}\,\beta_{x,y}^{out}}{1+\alpha_{x,y}^{out2}} \overset{\alpha_{x,y}^{out} \gg 1}{\approx} \frac{\beta_{x,y}^{out}}{\alpha_{x,y}^{out}}\,, \tag{11}$$

[3] It is worth mentioning that this strategy is not operational in the existing machine due to the fact that the nominal LHC optics does not possess the required properties in terms of phase advance from mid-arc to mid-arc and between mid-arc and interaction points of the ATLAS and CMS experiments.

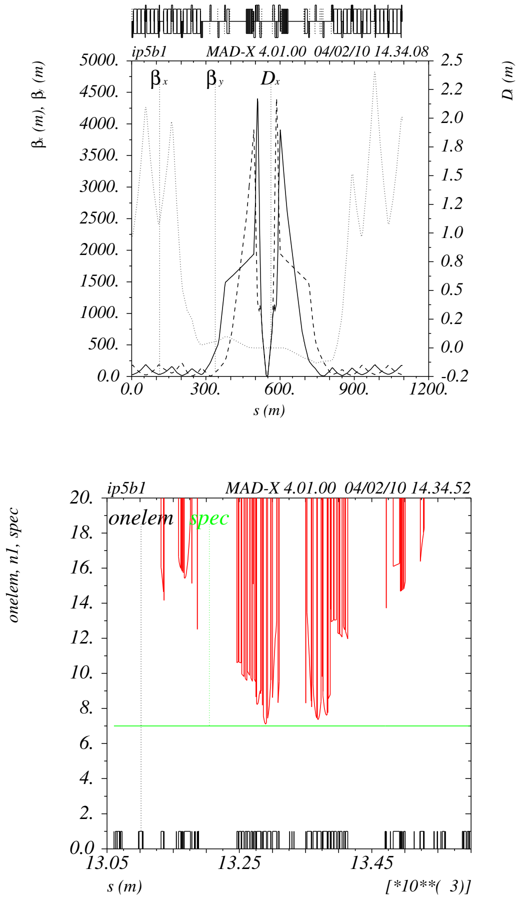


Figure 2: *Nominal collision optics ($\beta^* = 55$ cm) in IR1 and IR5 (from Q13.L to Q13.R) and typical aperture plot from Q7.L to Q7.R at 7 TeV.*

with $\beta_{x,y}^{out}$ and $\alpha_{x,y}^{out} \equiv -1/2 \times \left(d\beta_{x,y}^{out}/ds\right)$ denoting the Twiss parameters at the exit of Q3 (non-IP side). In each of the two planes, this parameter would then determine the position of an hypothetical waist of the β-function on the non-IP side of the triplet, assuming of course all matching section and dispersion suppressor quadrupoles switched off. In view of the above formula, the P parameter of the inner triplet is almost independent of β^* when the optics is squeezed. At low β^*, this invariant then only depends on the detailed layout of the inner triplet (magnetic lengths, interconnect lengths) and possible small gradient unbalances ($\lesssim 1-2$ T/m) imposed between Q1, Q2 and/or Q3. More precisely, while the β-functions $\beta_{x,y}^{out}$ at the IT exit are quite rigid quantities for a given β^* and operating gradient G of the inner triplet, their convergence (Twiss parameter $\alpha_{x,y}^{out}$) can be more or less arbitrarily chosen via a fine tuning of the layout and/or powering scheme of the inner triplet. Therefore, in the plane relevant for the aperture of the matching section (i.e. the vertical plane for beam1 on the right side of the IR, conversely for the left side and conversely for beam2 due to the optics antisymmetry of the LHC insertions, see Fig. 2), the lowest is the parameter P, the highest is the convergence of the β-function at the triplet exit and then the better is the mechanical acceptance of the matching section. On the other hand a triplet with a too short cofocal length (ideally corresponding to waist of the β-functions at Q4) may no longer be matchable to the LHC arcs unless deeply modifying the layout of the matching section. For the LHC low-β insertions, the limit is reached in practice when some magnets of the dispersion suppressor (typically Q7) reaches their nominal strength and/or some quadrupoles of the matching section go to extremely low field (typically Q5 and Q6).

More quantitatively, the layout of the existing triplet corresponds to a rather large parameter P of the order of 1 km (in the plane impacting on the mechanical acceptance of the MS), which then leads to a β-function of the order of 1500m and 900m in the MQY and MQM type magnets Q4 and Q5, respectively (see Fig. 2), for a peak β-function of $\beta_{IT}^{max} \sim 4.5$ km reached in the inner triplet. In such a configuration, the optics is found to be extremely flexible in the sens that collision optics with a β^* as low as 15 cm [5] can actually be matched while still fulfilling the nominal gradient limits of the IR quadrupoles but then, obviously, exceeding other limits in this case (MS and IT aperture and chromatic aberrations). In this respect, designing the layout of the new inner triplet with a similar cofocal length would be natural goal for the new insertion and gives actually quite a lot of flexibility in terms of gradients of the IR quadrupoles. However, as illustrated in Fig. 3, severe aperture bottle-necks are then observed in the matching section at the locations of the TAN, D2, Q4 and Q5.

At constant matching section (i.e. layout and magnet aperture), there is then no other choice than tuning the layout of the new triplet to a shorter or much shorter cofocal length, sacrificing the optics flexibility to the optimization of the mechanical acceptance of the matching section. By readjusting by 10 to 30 cm the magnetic or interconnect lengths of the inner triplet quadrupoles, it is then quite easy to reach short enough cofocal lengths, typically down to $\sim$ 350 m for a β_{IT}^{max} of the order of 12 km. In such a configuration, the mechanical acceptance of the matching section can be preserved (except for the TAN), while still finding a solution for the optics within the gradient limits of the IR quadrupoles (see Fig. 4). However such a compromise between MS aperture and IR quadrupole gradients using "low-P optics" configuration can no longer be found as soon as the peak β-function typically exceed 13 km in the inner triplet (i.e. $\beta^* \approx 25$ cm at a gradient of 120 T/m for the new IT) or even only 12 km ($\beta^* \approx 27$ cm) taking into account additional matching constraints imposed on the left and right phase advances of the insertion and related to the chromatic correction of the new triplet (see later):

$$\beta_{IT}^{max} \lesssim 12\,\text{km (MS aperture and IR quad. strength).} \quad (12)$$

Operating the machine with a margin of only 10% below this limit, that is with a β_{IT}^{max} not larger than 10.8 km (corresponding to $\beta^* \geq 30$ cm for the new IT), looks therefore

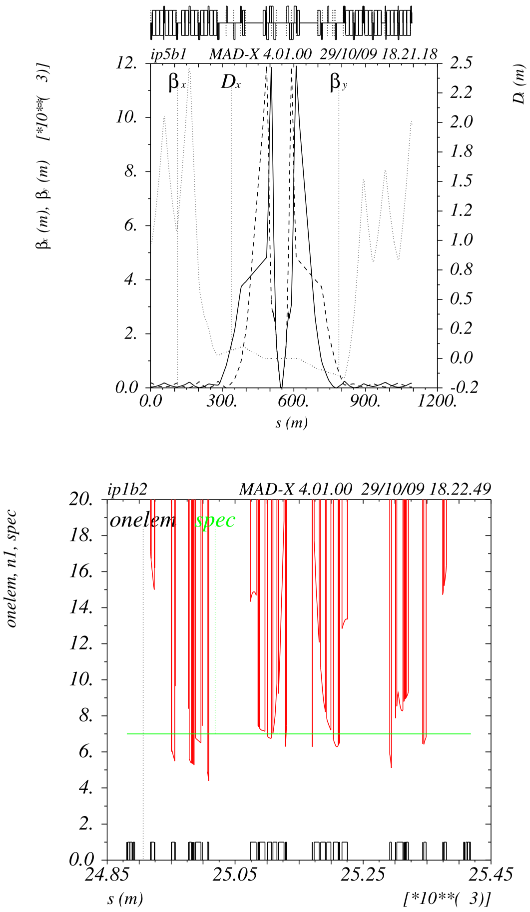


Figure 3: *"High-P optics" configuration ($P \sim 900$ m) for the new triplet and corresponding aperture plot from Q7.L to Q7.R (worst case obtained for beam2 in IR1). Severe aperture restrictions are observed in the matching section. As already announced, a peak β-function of the order of 12 km in the inner triplet slightly exceeds the limit imposed by the 120 mm coil aperture of the new low-β quadrupoles.*

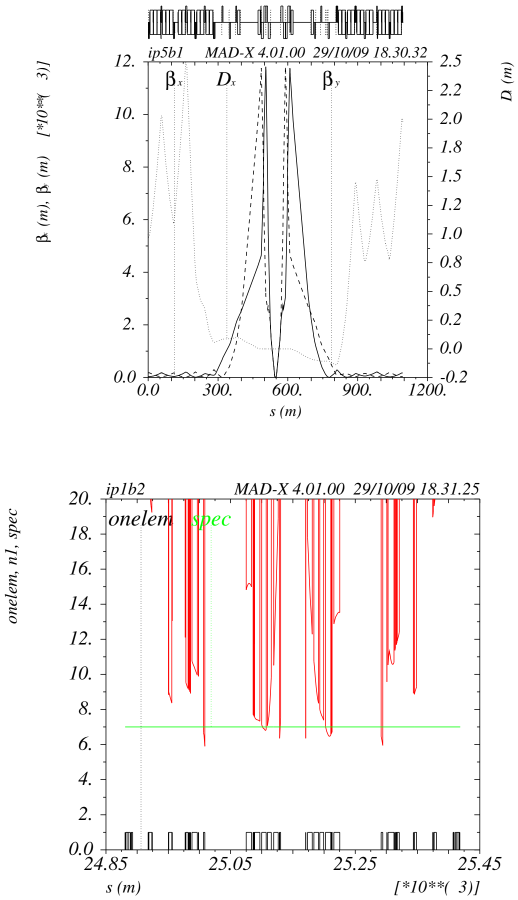


Figure 4: *"Low-P optics" configuration ($P \sim 350$ m) for the new triplet and corresponding aperture plot from Q7.L to Q7.R (worst case obtained for beam2 in IR1). The mechanical acceptance of the matching section is preserved (except at the TAN) but the gradients of Q5, Q6 and Q7 are close to the limits. As already announced, a peak β-function of the order of 12 km in the inner triplet slightly exceeds the limit imposed by the 120 mm coil aperture of the new low-β quadrupoles.*

already challenging.

It is then clear that new magnets with larger aperture are required in the matching section as soon as the target β^* corresponds to a peak β-function higher than 12-13 km in the inner triplet. This is however beyond the mandate of the Phase-I project where one of the main guidelines is to maximize the use of the existing LHC infrastructure except, obviously, concerning the inner triplet and other adjacent equipments such as the TAS, the separation dipole D1 and then, more recently, the TAN.

On the other hand, in order to preserve some optics flexibility while operating the machine with a β_{IT}^{max} of the order of 11-12 km ($\beta^* = 27 - 30$ cm), a satisfactory compromise can still be found by "re-adjusting" the layout of the existing matching section to the new length of the inner triplet (typically pushing the D2-Q4 and Q5 assemblies by 10-15 m towards the arcs) and, eventually, by re-optimizing the beam-screen orientation in the existing D2, Q4 and Q5 magnets [6]. In 2008, the Phase-I conceptual review [10] concluded however that such an intervention was also not compatible with the agenda of the project.

Crossing angle

The crossing angle is without any doubt a critical parameter if the beam-beam effects become dominant, a fortiori at higher than nominal intensity, and a fortiori for the new triplet, which is longer than the existing one and then induces an increase of the number of parasitic beam-beam encounters on either side of the IP (see later). Preserving a nominal normalised crossing angle of the order of 10σ for the minimum possible β^* (that is a full crossing angle of

$\theta_c = 410\,\mu$rad for $\beta^* = 30$ cm compared to $\theta_c = 285\,\mu$rad for the nominal LHC collision optics) or leaving open the possibility to operate the machine with even higher crossing angle at intermediate β^* (e.g. $\sim 16\sigma$ corresponding to $\theta_c = 560\,\mu$rad for $\beta^* = 40$ cm) will then inevitably use a big fraction of if not all the margins of the orbit corrector magnets participating to the crossing scheme (MCBY and MCBC magnets at Q4 and Q5/Q6 respectively). This is even more true for the "low-P" configuration which is imposed on the optics of the new insertions (see previous sub-section) where the peak β-function is more than doubled in the inner triplet while the β-functions at Q4, Q5 and Q6 are more moderately increased with respect to the nominal LHC collision optics.

More quantitatively, assuming that the new triplet will be equipped with three pairs of H/V orbit correctors (which guaranties an almost local correction of the IT misalignment with only a marginal contribution coming from the non-common orbit correctors at Q4, Q5 and Q6), and preserving 50% of the strength of the MCBC correctors at Q5 and Q6 (which, by design, must also participate to the correction of the closed orbit leaking from the dispersion suppressor), the limit found for the maximum possible full crossing angle is of the order of [9]

$$\theta_c^{max} \lesssim 560\,\mu\text{rad (MCBY strength limit).} \tag{13}$$

Then, it is worth mentioning that such a crossing angle does not offer any margin left for performing Vernier scans or IP steering at 7 TeV, which are also known to be key ingredients to optimize the machine performance in operation.

To summarize, not only an optimized orbit correction scheme shall be foreseen for the new triplet [9], but appropriate steps must also be taken in order to reinforce the non-common orbit correctors, essentially the MCBY's at Q4, in order to guaranty sufficient margins when operating the machine with a full crossing angle as high as $\theta_c \sim 0.5$ mrad, that is almost doubled w.r.t. to the nominal LHC crossing angle of 285 μrad. Additional dipole corrector magnets are however not yet included in the baseline of the Phase-I project.

Chromatic aberrations

Reducing β^* inevitably increases the chromatic aberrations induced by the inner triplet, in terms of linear and non-linear chromaticities such as Q'' and Q''', but also in terms of chromatic variations of the β-functions (so-called "off-momentum β-beating"). In order to evaluate any degradation with respect to the nominal LHC optics, it is relevant to introduce the following quantity:

$$I_{x,y} = \mp \int_{IT} ds K(s) \beta_{x,y}(s) \,, \tag{14}$$

where $K(s)$ represents the normalized strengths of the inner triplet quadrupoles. At constant l^* (distance between the IP and the entry of Q1), these integrals are found to scale approximately with the peak β-function β_{IT}^{max} reached in the inner triplet, that is inversely proportionally to β^* and to the square root of the IT gradient (see Eq. 1):

$$I_{x,y} \propto \frac{1}{\beta^* \sqrt{G}} \propto \beta_{IT}^{max} \,. \tag{15}$$

Linear chromaticity. Within a factor of 4π, the integrals $I_{x,y}$ give directly the contribution of the inner triplet to the linear chromaticity of the ring, that is for instance

$$\begin{array}{lcl} Q'_{IT}\,(\beta^* = 55\,\text{cm};\ G = 205\,\text{T/m}) & = & 25\,\text{units and} \\ Q'_{IT}\,(\beta^* = 30\,\text{cm};\ G = 120\,\text{T/m}) & = & 58\,\text{units}\,, \end{array}$$

obtained with the existing (205 T/m) and new (120 T/m) inner triplet and for the nominal and new collision optics with $\beta^* = 55$ cm and $\beta^* = 30$ cm, respectively. A degradation by a factor of more than 2 is then expected when β^* is reduced by a factor of less than 2 with respect to the nominal LHC collision optics. The chromaticity correction system of the LHC was however designed to be able to compensate for the linear chromaticity induced by four low-β insertions squeezed to $\beta^* = 25$ cm [15] (i.e. corresponding to β_{IT}^{max} of about 10 km for the existing triplets). The strength of the lattice sextupoles is then more than sufficient to correct the contribution of the four new triplets (two high luminosity insertions) to the linear chromaticity of the ring, down to a β^* of 30 cm or even well below.

Off-momentum β-beating and non-linear chromaticity. The other chromatic aberrations induced by the inner triplets scale with more or less high powers of β_{IT}^{max} depending on the effect under consideration:

$$\begin{array}{l} Q''_{x,y} \propto I_{x,y}^2 \propto (\beta_{IT}^{max})^2 \,,\ Q''' \propto (\beta_{IT}^{max})^3 \,,\ \ldots \\ \partial\beta/\partial\delta \propto \beta_{IT}^{max} \,,\ \partial^2\beta/\partial\delta^2 \propto (\beta_{IT}^{max})^2 \,,\ \ldots \,. \end{array}$$

A net degradation is then expected with the new inner triplet for which the peak β-function is more than doubled compared to $\beta_{IT}^{max} \approx 4.5$ km reached in the existing IT. One possible and well-known strategy would consist in imposing in both planes a phase advance of $\pi/2$ [π] between the two high luminosity insertions IR1 and IR5. In this configuration, a self-compensation takes place between the two insertions, canceling the second order chromaticity Q" and minimizing the off-momentum β-beating at least to first order in δ and in the second half of the LHC ring, let say in between IP5 and IP1. This strategy is not foreseen for the latest optics and layout version of the LHC (V6.503 [16]) but could be easily implemented by retuning the betatron phase advances in the arc cells of several LHC sectors. Trying this strategy for the new triplet, it is then obvious that the off-momentum β-beating can be minimized in only one of the two collimation insertions (IR7 in our case). It is then maximized in the other collimation insertion, possibly reaching 160% at a momentum deviation of $\delta_p = 10^{-3}$ (see Fig. 5). This value is considered large enough to corrupt the hierarchy of the multi-stage collimation system of the LHC [17], at least in IR3. In addition, while the second order

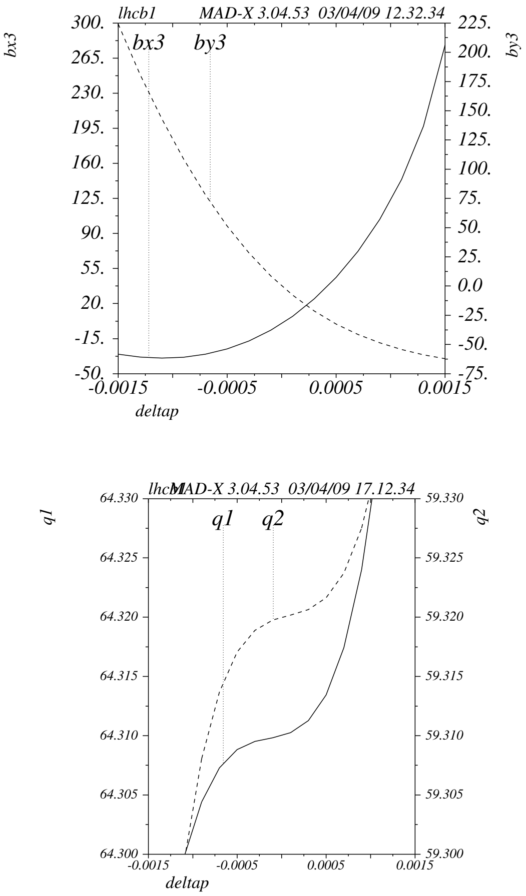


Figure 5: *Typical chromatic variations of the β-functions [%] in between IP1 and IP5, in particular in the momentum collimation insertion IR3 (top), and chromatic variations of the tunes (linear chromaticity matched to 2 units). The horizontal and vertical betatron phase advances are assumed to be matched to $\pi/2$ $[\pi]$ between IP1 and IP5; the squeezed optics of IR1 and IR5 are supposed to be strictly identical (with $\beta_{IT}^{max} \approx 12$ km in the new triplets).*

chromaticity Q'' can be nicely canceled via the IR phasing strategy, the third order chromaticity Q''' is large enough to push the working point towards the third order resonances at a momentum deviation of only one permil (see Fig. 5). Even if the half height of the nominal RF bucket is about three times less at flat top energy ($\delta_{bucket} = 0.36 \times 10^{-3}$), this effect will then impose rather tight constraints on the possibility of performing off-momentum beam measurements when the optics is squeezed. A rather precise interlock system on the beam energy will also have to be set up, with a level of accuracy of the order of a few 10^{-4} and therefore possible implications on the machine operation at flat top energy. Finally it is worth mentioning that the efficiency of the IR phasing strategy can be easily corrupted in the presence of β-beating or β^* unbalance between the two high luminosity insertions IR1 and IR5. In particular this

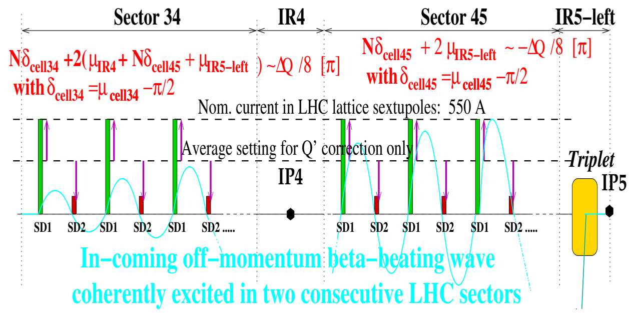


Figure 6: *"Chromatic phasing conditions" w.r.t. IP5 (a simplified version without using the tune shift quadrupoles MQT's, see later) and schematic powering scheme of the (SD) sextupole families in arcs 34 and 45 in order to excite coherently a (vertical) off-momentum β-beating wave.*

strategy pre-supposes obviously a simultaneous squeeze of the two insertions.

Correction strategy and global impact on the LHC optics. The correction of the chromatic aberrations induced by the inner triplets in collision has been an unsolved well-known issue during the last two decades. Pending a solution to this problem, specific sextupole corrector circuits were nevertheless foreseen in the early design of the machine and are actually installed in the LHC: two interleaved sextupole families per plane in each of the 8 LHC sectors (instead of one single family per plane which is actually needed for the only correction of the linear chromaticity). However, considered for a long time at the limit of acceptability for the nominal LHC, no clear strategy was proposed to correct these effects: in particular how to make the best use of the 32 lattice sextupole circuits per beam available in the LHC and, then, what could be the impact in terms of strength requirements for the arc sextupoles but also in terms of optics constraints for the overall machine?

Only very recently, a complete solution was found [18] based on an up and down excitation scheme of the focusing (SF) and defocusing (SD) lattice sextupoles around an average value (the same for all SF and SD families) which is tuned to correct the linear chromaticity of the ring (see Fig. 6). As a result, a wave of off-momentum β-beating is generated in each of the 8 LHC sectors. Concerning the amplitude of the off-momentum β-beating induced, above a certain β_{IT}^{max} of the order of 5 km (i.e. below a certain β^*), two sectors of sextupoles are needed to compensate for the "chromatic betatron kick" given by one single triplet. Then half of the defocusing sextupole circuits[4] are pushed up to nominal current (550A) as soon as the the peak β-function reaches the following limit in the inner triplet:

$$\beta_{IT}^{max} \lesssim 11\,\text{km} \;\; \text{(550A in the lattice sextupoles)}. \quad (16)$$

[4]A specificity of the LHC is that the defocusing sextupoles SD's are approximately twice less efficient than the focusing sextupoles SF's due to the fact that the dispersion function is halved at the arc QD's while the SD's and SF's have exactly the same magnetic length.

This limit corresponds to a β^* of the order of 30 cm for the new triplet ($G \sim 120$T/m). To summarise, while the LHC chromatic correction scheme was dimensioned based on the compensation, still with some margin, of the *linear chromaticity* induced by four low-β insertions running simultaneously at a β^* of 25 cm, a *full chromatic correction*, including as well the non-linear chromaticity and the off-momentum β-beating, limits severely the operational mode of the machine in collision, to only two new high-luminosity insertions running at a minimum β^* of 30 cm and with strictly no margin. The reason is simple. The operating gradient of the new triplet is reduced by about 70% (which means an increase of the $I_{x,y}$ integrals by about 30% at constant β^*, see Eq. 15) and, as illustrated in Fig. 6, only half of the sextupole circuits participate effectively to the chromatic correction of the inner triplets.

This being said, contrary the Q' correction, the compensation of the chromatic aberrations requires that specific phasing conditions are fulfilled all around of the ring.
First of all, the phase advance in the LHC arc cells shall be as close as possible to $\pi/2$. This target maximizes the coherence of the off-momentum β-beating waves excited in the 8 LHC sectors but also minimizes any possible side effects as the residual second order chromaticity induced by the lattice sextupole themselves [18]:

$$Q''_{sext} \approx \frac{1}{4\pi} \int ds\, K_2(s)\, D_x(s)\, \left(\partial\beta/\partial\delta\right)_{(\delta=0;s)} \,, \quad (17)$$

where $K_2(s)$ and $D_x(s)$ denotes the normalised sextupole strength and the dispersion function along the machine, and $\partial_\delta\beta(\delta=0;s)$ represents the first order chromatic derivative of the β functions at the sextupole locations. This derivative is null at all the sextupoles for a phase advance of strictly $\pi/2$ in the FODO cells of the LHC arcs. In this case the chromatic correction does not generate any additional second order chromaticity according to Eq. 17.
Then two consecutive sectors participating to the chromatic correction of one given triplet (e.g. sectors 34 and 45 in Fig. 6) must combine in phase with respect to the off-momentum β-beating wave that each of them generates separately. Finally the resulting overall wave shall arrive in quadrature of phase at the location of the inner triplet for a proper compensation of the betatron chromatic kick induced by the low-β quadrupoles. The correction of the chromatic aberrations therefore requires to completely revisit the nominal LHC optics, with specific phasing conditions imposed on both beam and connecting together

- the betatron phase advances in the arc cells of the 8 LHC sectors,
- the betatron phase advances across the four insertions IR2, IR4, IR6 and IR8 (from Q13.L to Q13.R) which plays the role of trombone insertions w.r.t. to the off-momentum β-beating,
- the left and right phase advances (from Q13.L to the IP and from the IP to Q13.R) of the two high luminosity insertions IR1 and IR5,
- and, last but not least, possibly non-zero settings imposed to the tune shift quadrupoles MQT (from Q14 to Q22) which, as soon as the LHC insertions have reached their tunability limits, remains the only available knobs in order to adjust the betatron phases of each beam individually.

These phasing conditions are detailed in Ref. [18] and reported on Fig. 6, illustrating as well that still some flexibility is left for a fine tuning of the working point.

A new overall LHC optics has then be built up accordingly [19], which was relatively tricky as explained hereafter. Without going too much into the details, the main differences with the nominal optics is a tune split reduced from 5 to 3 while preserving the fractional part of the working point ($Q_{x,y} = 63.28/60.31$ for the new optics at injection instead of 64.28/59.31 for the nominal LHC optics). This reduction is due to the fact that the arc cell phase advances are now closer to $\pi/2$ for the new optics. As explained previously, horizontal and vertical phase advances of strictly $\pi/2$ in the LHC arc cells or, let say, even smaller tune split would have been preferable for the chromatic correction of the inner triplet. However, in order to satisfy the phasing conditions reported on Fig. 6, a "chromatic aberration free optics" with even smaller tune split has been found to be out of reach due to the accumulation of several reasons:

- the limited tunability of the trombone insertions IR2, IR4, IR6 and IR8 driven by aperture related constraints at injection (essentially IR4 and IR6 due to missing quadrupoles, Q4 and Q7, respectively),
- the quasi-null flexibility of the collimation insertions IR3 and IR7 which therefore cannot be used as global knobs to preserve the fractional part of the betatron tunes,
- and, last but not least, the quite rigid left and right phase advances of the high luminosity insertions in collision which, in the horizontal plane, depends strongly on the layout of the triplet itself, more precisely on its co-focal length that is the P parameter introduced previously in Eq. 11.

The potential of this new optics is illustrated in Fig. 7. After an active correction by the lattice sextupoles, the off-momentum β-beating envelop is nicely vanishing in the two collimation insertions IR3 and IR7 but also in the new inner triplets equipping IR1 and IR5. The chromatic variations of the betatron tunes become almost linear up to momentum deviation of 1.5 permil and after an eventual fine tuning of the residual Q'' using the Landau octupoles of the LHC arcs (see next section and Ref. [18] for more details).

A complete solution can then be found "in extremis" for the correction of the large chromatic aberrations induced by the new inner triplet in collision. This however limits the minimum possible β^* to 30 cm when half of the defocusing sextupole circuits shall be powered with a current very

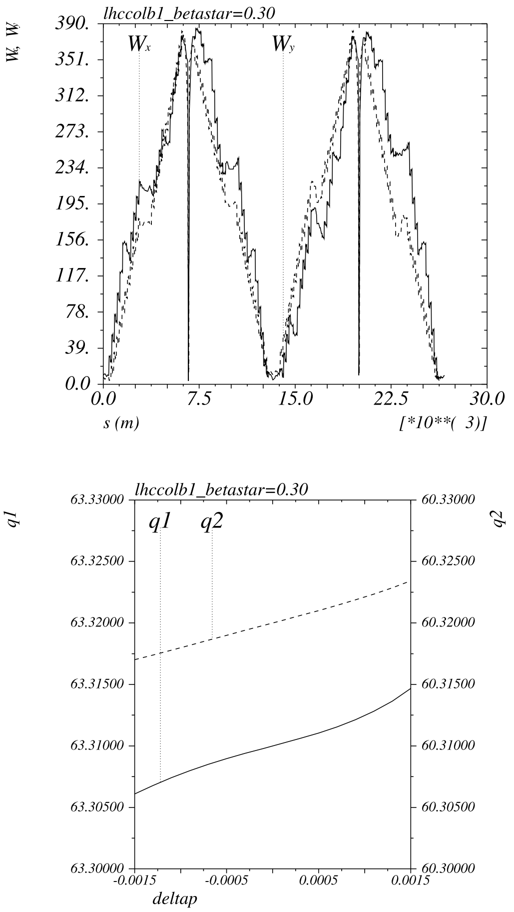


Figure 7: *Off-momentum β-beat envelop ($|(\partial_\delta \beta(\delta=0;s)|$) along the LHC ring (top) and chromatic variation of the betatron tunes (bottom) in collision ($\beta^* = 30$ cm) for the SLHCV2.0 optics and layout [19].*

close to nominal. Unless these well-identified families are recommissioned with higher than nominal current, ideally up to 600A or even beyond, linear optics distortions (typically phase errors randomly distributed in the machine) may then further limit the minimum possible β^* in the real machine, to let say $\beta^*_{min} \approx 35 - 40$cm.

Field quality

While the field quality of the new triplet and of the new D1 separation dipole has no impact on the dynamic aperture (DA) of the machine at injection, the situation is quite different in collision when the optics is squeezed in the two high luminosity insertions IR1 and IR5. As far as only random multipoles are concerned, general scaling laws predict an improvement of the field quality with the coil aperture of the new magnets [20]:

$$b_n \left(R_r = \alpha\, \mathrm{Coil_{ID}}\right) \propto \frac{1}{\mathrm{Coil_{ID}}}\,, \tag{18}$$

with R_r a reference radius corresponding to a given fraction of the coil aperture, typically one third (that is a reference radius of 40 mm for the new triplet). Starting from the field quality measured in the existing MQXA and MQXB low-β quadrupoles and applying the above scaling law to extrapolate the field quality of the new triplet, assuming that any possible sources of systematic multipoles could be detected early enough and then corrected during the production, and neglecting any possible contributions coming from the D1 separation dipole, preliminary dynamic aperture studies showed extremely encouraging results [21]. In particular, a very decent dynamic aperture of the order of or larger than 12σ was found with a 130 mm aperture triplet, operating with a β_{IT}^{max} of the order of 12-13 km, and without any specific correction. A minimal correction scheme containing only shew quadrupole and sextupole corrector magnets, MQSX and MCSX, respectively, was then included in the first schematic layout of the new triplet [10].

Then less optimistic estimates were derived for the field quality of the new triplets, based on the multipole components measured in the main quadrupoles MQ of the LHC (since the new IT will be equipped with the same Nb-Ti cables) and then rescaled to the 120 mm aperture of the new MQXC quadrupoles. Possible non-zero systematic multipoles (uncertainty) were also included in the field error table expected for the new triplet [22]. Finally the new superconducting separation dipole [23] was also taken into account in the simulations, being said that very significant low order multipole errors (i.e. from one unit up to one permil) such as a_2, a_3, b_3 and b_5 are presently expected in the new D1. Under these conditions, a dynamic aperture as low as 6σ cannot be excluded (see red solid lines in Fig. 8). It was then made very clear that

- the new IT should be equipped at least with the same corrector package as the one installed in the existing triplet, that is not only a_2 and b_3 but also a_3, a_4, b_4 and b_6 corrector coils and, in addition,
- an effort should be made to improve the field quality of the new triplet and D1 in order to met a target dynamic aperture of about 12σ in collision [24].

New triplet. A preliminary target error table has then been established for the new triplet, starting from the field quality measured in the existing MQXB type magnets and then applying a rescaling at constant non-linear kick:

$$\frac{[b_n(R_{r_\mathrm{new}})]_\mathrm{Target}}{[b_n(R_{r_\mathrm{old}})]_\mathrm{MQXB}} \equiv \left(\frac{(\beta_{IT}^{max})_\mathrm{old}}{(\beta_{IT}^{max})_\mathrm{new}}\right)^{n/2} \times \left(\frac{R_{r_\mathrm{new}}}{R_{r_\mathrm{old}}}\right)^{n-2}\,, \tag{19}$$

with $R_{r_\mathrm{old}} \equiv 17$ mm and $R_{r_\mathrm{new}} \equiv 40$ mm denoting the reference radius used to define the multipole components of the MQXB and new MQXC type magnets, and where $(\beta_{IT}^{max})_\mathrm{new} = 4.5$ km and $(\beta_{IT}^{max})_\mathrm{new} = 11$ km represent the peak β-functions reached in the existing triplet and in the new one when operating the machine at a β^* of 55 cm

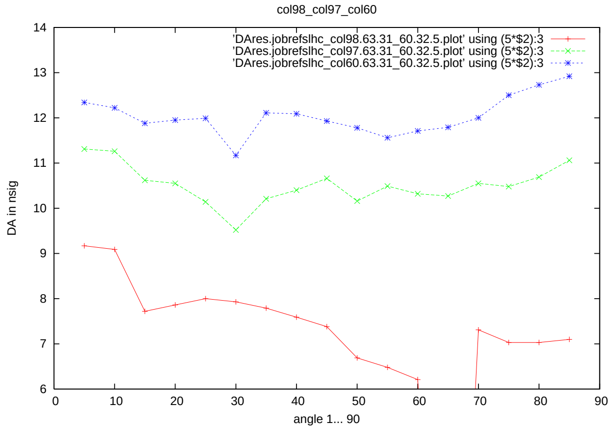


Figure 8: *Minimum 100'000 turns dynamic aperture* $[\sigma]$ *of the sLHC Phase-I in collision (*$\beta^* = 30$ *cm at IP1 and IP5) as a function of the phase space angle* $[°]$*, obtained for 60 different error realizations in the new IT and D1 (seeds). From bottom to top, the following three cases have been considered: a-) expected error table for the new triplet[22] and D1[23] and minimal correction scheme (*a_2 *and* b_3*) as proposed in [10], b-) idem but assuming a more complete set of low-order multipole corrector magnets (*a_2, b_3, a_3, b_4, a_4, b_6*), c-) idem but assuming a better field quality for the triplet (derived from Eq. 19 for the multipoles of order* $n \leq 6$*) and using the so-called error table target10 for the new D1 [26]. Courtesy of B. Holzer.*

and 30 cm, respectively. A target DA of about 12σ is then easily reached under these conditions (blue dotted line in Fig. 8). The strategy is presently to relax one by one the target multipoles obtained via the above formula, in order to identify the ones which are really detrimental for the dynamic aperture of the machine in collision and then start an iterative process with the magnet builders. The work should be completed and published in the coming months but preliminary results seems to indicate that only a few low order multipoles are actually found critical for the DA in collision and would need to be further optimized, applying a reduction factor of not more than 2 with respect to the error table given in Ref. [22]. This is in particular the case for the b_6 uncertainty where about 1 unit seems to be tolerable compared to 1.77 units expected in Ref. [22], or for random and/or systematic multipoles such as a_5, b_5 or a_6 for which no specific correction is presently foreseen [25].

D1 separation dipole. The new separation dipole D1 contains two superconducting DX RHIC magnets [23]. It is found to be critical not only for its possible impact on the dynamic aperture in collision but also and mainly for the rather large linear imperfections that it may generate when the optics is squeezed and in the presence of the crossing scheme. In this respect, a detailed target field error table has been established for the new D1 [26], taking into account the possible linear optics distortions directly induced by its a_2 and b_2 components but also via the feed-down

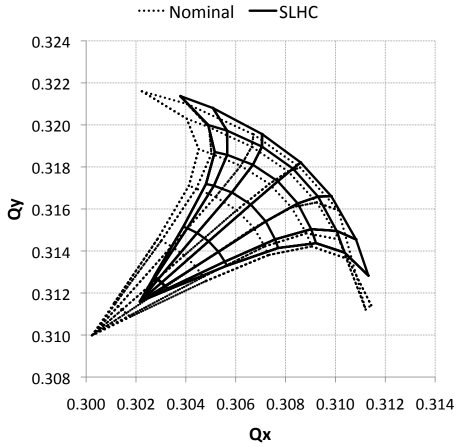


Figure 9: *Two-dimensional tune distribution versus amplitude (particles with betatron amplitudes up to* $6\,\sigma$ *are showed) at nominal intensity per bunch (*$N_b = 1.15\times10^{11}$*). Comparison between the nominal LHC collision optics (*$\beta^* = 55$ *cm at IP1 and IP5,* $\beta^* = 10$ *m at IP2 and IP8, halo collision in IP2) and the new optics and layout SLHCV2.0 [19] with* $\beta^* = 30$ *cm at IP1 and IP5 (and no change of configuration in IP2 and IP8). Courtesy of E. Laface.*

effects from b_3 and a_3. The latter are particularly relevant since they represent a dynamic source of tune shift, coupling or β-beating during a fill, when operating Vernier scans, fine tuning the crossing angle or simply collapsing the parallel separation in order to put the two beams into collision. While a maximum of 2-3 units is still tolerable for a_2, the level of 1 unit shall be reached for the b_2, b_3 and a_3 harmonics, that is a factor of 2 to 6 below the 3σ level deduced from the D1 error table presented in Ref. [23]. It is therefore not yet clear whether a simple sorting (pairing) strategy for the two DX magnets forming the D1 assembly will be sufficient or whether additional actions will be needed in order to meet the above targets.

Beam-beam effects

Several indicators are generally used to qualify the beam-beam effect in circular colliders. As far as only incoherent effects are concerned, the first one is the well-known tune footprint (beam-beam induced tune shift or tune spread) which, at constant intensity per bunch and at constant normalised crossing angle, is reduced when operating the machine at lower β^* (see Fig. 9). In the case of the LHC Insertion Upgrade Phase-I, the following scaling law can be used:

$$\Delta Q_{bb}^{\mathrm{IR8}} + \Delta Q_{bb}^{\mathrm{IR1}} + \Delta Q_{bb}^{\mathrm{IR5}} \propto \frac{N_b}{\gamma\epsilon} \times \left(1 + \frac{2}{\sqrt{1+\phi_w^2}}\right), \quad (20)$$

using the same notations as the ones introduced in Eq. 9, assuming an alternated HV or VH crossing scheme in IR1 and IR5, supposing that Alice (IR2) operates in halo collision and that the optics is not squeezed ($\beta^* \approx 10$ m) for the LHCb experiment (IR8).

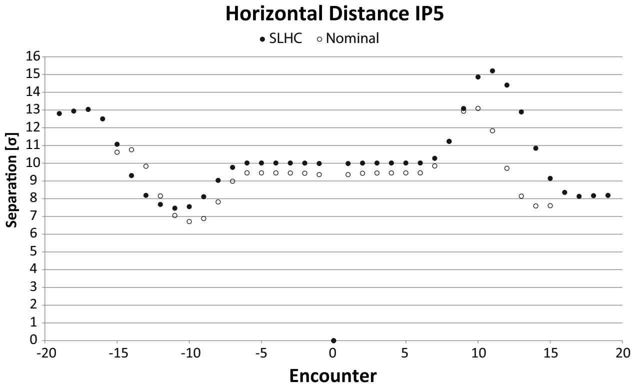


Figure 10: *Normalised beam-beam separation up to D1 in IR5 (horizontal crossing) for the nominal LHC ($\theta_c = 9.5\,\sigma$), and for the new collision optics ($\theta_c = 10\,\sigma$) and latest layout of the new triplet. In the second case, the last two parasitic encounters before D1 have been artificially removed. Courtesy of E. Laface.*

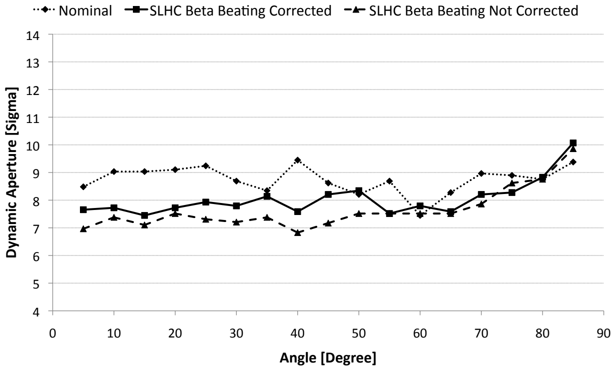


Figure 11: *1'000'000 turns dynamic aperture of the machine in collision considering only the beam-beam effect (long-range and head-on) at nominal intensity per bunch ($N_b = 1.15 \times 10^{11}$). Comparison between the nominal LHC optics and layout (dotted line) and the new optics and layout of IR1 and IR5 with (solid line) and without (dashed line) activating the correction of the chromatic aberrations. It is assumed that the layout of the new triplet can be optimized such that only 19 parasitic beam-beam encounters take place on either side of the IP up to D1 (compared to 15 in the case of the existing low-β insertions IR1 and IR5). Courtesy of E. Laface.*

Another extremely relevant indicator is the degradation of the dynamic aperture due to the beam-beam effects and, in particular, due to the long-range beam-beam interactions. In the case of the LHC, these interactions take place on either side of the IP till D1 when the two beams start to be fully separated. For the nominal 25 ns bunch spacing of the LHC beam, the existing high luminosity insertions IR1 and IR5 contain 15 parasitic beam-beam encounters, spaced by 3.74 m, up to the entry of D1. The latest layout of the new triplet corresponds to a total of 21 parasitic encounters on either side of the IP (see later). This number will possibly rise to 22 when additional non-linear corrector magnets (see previous sub-section) will be added the IT corrector package (CP) located on the non-IP side of Q3 (see Fig. 12). A more reasonable target of 18 or possibly 19 should however be reachable in view of the moderate lengthening of the new triplet by about 10 m and taking into account that the triplet corrector magnets shall also be longer (at constant integrated strength but larger aperture). Dedicated dynamic aperture studies have then been performed both using the nominal collision optics and layout of the LHC (V6.503 [16]) and the new optics SLHCV2.0 [19], switching off any possible field imperfections in the magnets of the ring and treating the beam-beam effects in the so-called "weak-strong approximation" [5]. Even if the above target of 19 parasitic encounters can be met, and taking into account the slight increase of the normalised crossing angle from $9.5\,\sigma$ to $10\,\sigma$ for the new collision optics (see Fig. 10), a net degradation of the dynamic aperture is observed, of the order of 1-1.5 σ at nominal intensity (see Fig 11). This reduction can however be mitigated activating the correction of the chromatic aberrations induced by the inner triplet (see Fig. 6) which possibly plays a significant role in terms of excitation of synchrotron-betatron resonances as soon as the beam-beam effect is switched on. More complete simulations combining the beam-beam effect and the multipole imperfections of the LHC magnets, in particular of the new IT and D1, will be presented at the end of the paper.

Two or three additional parasitic encounters, that is 21 or 22 instead of 19, will not represent a clear obstacle for the LHC IR Upgrade Phase-I. However, this will certainly not go in the right direction, in order to operate the machine with an as low as possible normalised crossing angle and therefore preserve the luminosity gain coming from the reduction of β^* (see Eq. 9).

A COMPLETE SOLUTION WITH $\beta^* \geq 30$ CM

Having integrated all the possible optics limitations described in the previous section, this section will describe the solution proposed for the IR Upgrade Phase-I, in terms of layout, optics and dynamic aperture at injection and in collision including or not the beam-beam effect.

Layout

Two different versions were developed in 2009 for the optics and layout of the new triplets. These two versions correspond to very similar peak β-function β_{IT}^{max}, of the order of 10.6-10.8 km at $\beta^* = 30$ cm, and P parameter of the order of 320 m (see Eq. 11). The distance between the

[5] In the "weak-strong" approximation, the beam-beam effect induced on the "weak" beam is modeled by installing single and multiple 4D beam-beam lenses at each of the parasitic encounters and around the four interaction points of the machine, respectively, in order to simulate the non-linear beam-beam kicks induced by the "strong" beam.

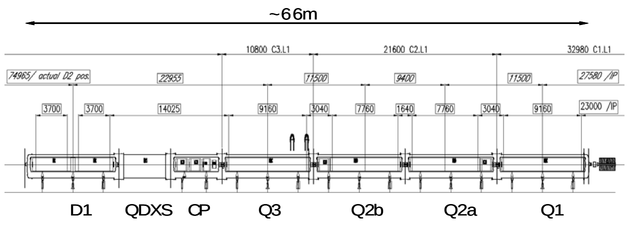


Figure 12: *Schematic layout of the new triplet. Courtesy of H. Prin*

IP and the magnetic entry of Q1 is assumed to be fixed to $l^* = 23$ m for the LHC IR Upgrade Phase-I.

New low-β quadrupoles MQXC and MQXD. As mentioned previously, the new triplet will have an aperture of 120 mm with an operating gradient ranging in between 120 T/m and 127 T/m [11] (80-85% of the short sample limit). The latest layout is based on a gradient of 123 T/m for Q1 and Q2 which has been fine tuned in order to find an acceptable compromise for the positioning of the bi-directionnal BPMS in each of the interconnects of the new triplet (see later). The gradient of Q3 is slightly lower (122.2 T/m) for optics related reasons (P parameter impacting on the gradients and the mechanical aperture of the matching section quadrupoles). Contrary to the first proposal of having exactly the same magnetic length for the four quadrupoles Q1, Q2a, Q2b and Q3 equipping the new triplet [10], it was rapidly agreed to stick to the design of the existing triplet with two different lengths for Q1/Q3 and Q2a/Q2b (9.145 m and 7.735 m, respectively, for the latest layout SLHCV2.0 [19], compared to 6.37m and 5.50m for the existing MQXA and MQXB type quadrupoles). Indeed, at constant β^*, the gain was of the order of 7-8% in terms of peak β-function reached in the inner triplet, therefore substantial due to the severe limitations imposed on this quantity as previously described.

Orbit corrector magnets and other triplet corrector. A corrector package (CP) will be installed on the non-IP side of Q3. This assembly will contain one pair of H/V orbit corrector magnets (MCBX), a skew quadrupole corrector MQSX and a sextupole corrector MCSX [10]. As mentioned previously, additional corrector coils such as a_3, a_4, b_4 and b_6 multipole corrector magnets have been found mandatory to preserve the dynamic aperture of the machine in collision. The latter are not yet implemented in the schematic layout showed in Fig. 12. Then, the main difference between the first and second IT layout, SLHCV1 and SLHCV2 developed in 2009, is the implementation of additional orbit corrector magnets inside the triplet itself, more precisely in the cold masses of Q2a (IP side) and Q2b (non IP side). In order to guaranty a local correction of the triplet misalignments, therefore of good quality and without interfering with the generation of the crossing scheme, as short as possible double plane orbit corrector magnets are highly desirable at those two locations [9]. Nested dipole correctors, based on epoxy-impregnated coils, as used in the present triplet, are however not considered appropriate for the performance goals of the Phase-I upgrade (1000 fb^{-1} life time). A specific R&D effort will be then deployed [27] in order to find an appropriate technical solution for the orbit correctors of the new triplet (about 1.5m long, offering an integrated strength of 1.5 Tm in both planes).

BPM. As for the four existing experimental insertions of the LHC, a slot just upstream the TAS in IR1 and IR5 will be reserved for a warm bidirectional BPM (BPMSW) which is considered as one of the most suitable instruments to find the collision. Then each interconnect of the new triplet will be standardized in order to host a cold bidirectionnal BPM (BPMS), that is four BPMS's per triplet in the Q1-Q2a, Q2a-Q2b, Q2b-Q3 and Q3-CP interconnects. Except for the BPMS in between Q1 and Q2a, the three other BPMS's are close or even very close to optimal positions, that is in between two parasitic beam-beam encounters with a tolerance estimated to ± 75 cm for the nominal machine (in order to preserve a measurement accuracy of the order of $\sim 50\mu$m in the presence of two nominal counter-rotating LHC beams, see e.g. [28]). Finally, it would be advisable to add a last BPM on the non-IP side of D1 which, combined with the BPMWB on the IP-side of D2 and the BPMS on the non-IP side of Q3, will offer a robust measurement method for the extremely sensitive parameter P of the inner triplet.

Separation dipole D1. The existing warm D1 magnets installed in the high luminosity insertions IR1 and IR5 do not offer enough aperture for the beam below a β^* of about 50 cm, especially when the crossing angle is chosen to be vertical. The proposal for Phase-I is based on a superconducting assembly containing two 3.7 m long RHIC DX magnets. This magnet will work at the 1.9K temperature of the inner triplet and will offer an integrated strength of about 30 Tm [29], increased with respect to 26.3 T/m needed for the existing D1 due to the lengthening of the new triplet and therefore the reduction of the distance between D1 and D2. While the mechanical acceptance of the new D1 (180mm ID) is more than sufficient compared to the beam aperture requirements[6], its field quality would need to be substantially optimize with respect to the present expectations and monitor with a very special care during the production (see [26] and previous discussion).

TAS, TAN and other protection devices. 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 D1 and D2. In particular the TAN becomes a severe aperture bottle-neck in the new insertion ($n_1 \sim 5.5$)

[6] A cold D1 equipped with the IT beam-screen would still give a normalised aperture of slightly more than $n_1 \sim 7$ at $\beta^* = 30$ cm.

when the crossing angle is chosen to be vertical and the optics is squeezed down to $\beta^* = 30$ cm (see later). As soon as the D1-D2 distance will be frozen, the cross-section of the new TAN will be specified together with the design of the new Y-chamber. New collimation devices will certainly be needed in the matching section, either to protect the dispersion suppressor from the out-going beam as already foreseen (TCL at Q5) or to protect Q5, Q4 and D2 from the in-coming beam. In this second case, loss maps studies are however not completed yet to fully justify the need (see e.g. [30]) and then to validate a possible remedy (e.g. TCT-like absorber installed upstream Q5).

Matching section. Except for additional collimation devices installed close to Q5 and possibly warm dipole corrector magnets added close to Q4 to reinforce the MCBY's (see previous discussion), the matching section is assumed to be kept unchanged for the LHC IR Upgrade Phase-I.

Other considerations. The latest layout of the new triplet corresponds to 21 parasitic beam-beam encounters on either side of the IP up to D1, out of which about 4 are located downstream Q3 considering a total length of about 14 m estimated for the corrector package (CP) and the triplet service module (QDXS). As mentioned above, this number will further increase when additional non-linear corrector magnets will be implemented in the design of the corrector package. Any specific measure will then be more than welcome to keep the IT-CP-D1 assembly as compact as possible, starting from a suitable solution with only a few nested corrector coils for the corrector package (e.g. MCBXHV, MQSX, MCSTX and MCOSX type magnets as in the existing triplet), envisaging a configuration where the CP and IT bus-bars would transit through D1 (QDXS installed on the non-IP side of D1), or even studying the pros and cons of a solution where the CP and D1 would occupy the same cryostat which would eliminate a second interconnect in between Q3 and D1.

Optics, crossing scheme and mechanical aperture of the new insertions

The main parameters related to the new inner triplet and to the injection and collision optics of the new insertions IR1 and IR5 are summarized in Tab. 2. A back-up collision optics with an higher β^* and a larger than $10\,\sigma$ normalised crossing angle is also mentioned. A detailed discussion concerning the gradients of the various quadrupoles of the new insertion will take place later on when the squeeze of the optics will be presented.

Injection. β^* is chosen to be 14 m at injection (see Fig. 13(a)) in order to limit the peak β-functions to be less than 250-300 m in the inner triplet (as in the present triplet with $\beta^* = 11$ m), and therefore minimise any possible impact of the IT and D1 field quality on the dynamic aperture of the machine at injection.

Parameters	Injection	Collision	Back-up
Energy [GeV]	450	7000	7000
Q1/Q2 gradient [T/m] (at 7 TeV)	119.01	123.00	122.81
Q3 gradient [T/m] (at 7 TeV)	119.01	122.22	122.22
β^* [m]	$\mathbf{14.00}$	$\mathbf{0.30}$	$\mathbf{0.40}$
β_{IT}^{max} [km]	0.3	10.8	8.1
Co-focal length P [m]	Irrelevant	312	334
$\Delta\mu_{x/y}^{\rm Tot}$ $[2\pi]$	$2.655/2.639$	$2.670/2.644$	
$\Delta\mu_{x/y}^{\rm L}$ $[2\pi]$ for beam1	Irrelevant	$1.070/1.754$	
$\Delta\mu_{x/y}^{\rm R}$ $[2\pi]$ for beam1	Irrelevant	$1.600/0.890$	
$\Delta\mu_{x/y}^{\rm L}$ $[2\pi]$ for beam2	Irrelevant	$1.605/0.890$	
$\Delta\mu_{x/y}^{\rm R}$ $[2\pi]$ for beam2	Irrelevant	$1.065/1.754$	
Full X-angle [μrad]	410	410	560
Full parallel sep. [mm]	5.0	1.5	1.5

Table 2: *Main optics parameters for the new insertions IR1 and IR5 at injection and in collision.*

Contrary to the collision optics, the left and right betatron phase advances of the insertion ($\Delta\mu_{x/y}^{\rm L/R}$ in Tab. 2) can be arbitrarily chosen. Only the overall phase across the insertion (namely $\Delta\mu_{x/y}^{\rm Tot}$ from Q13.L to Q13.R) is imposed by the choice of the working point.

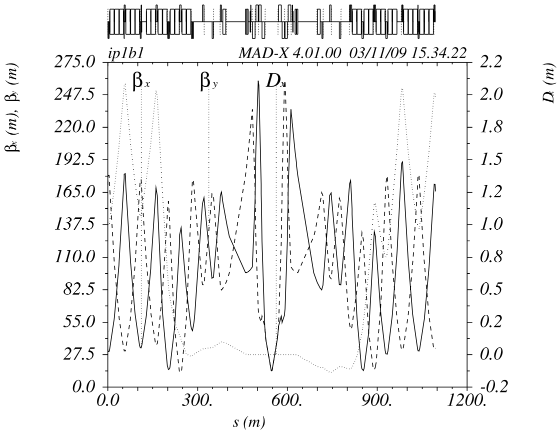
The full crossing angle is fixed to $\theta_c = 410\,\mu$rad, that is slightly more than $17\,\sigma$ for $\beta^* = 14$ m, and a full parallel separation of 5 mm is imposed at injection (see Fig. 13(b)).

As illustrated in Fig. 13(c), the mechanical aperture of the new IR exhibits the following properties:

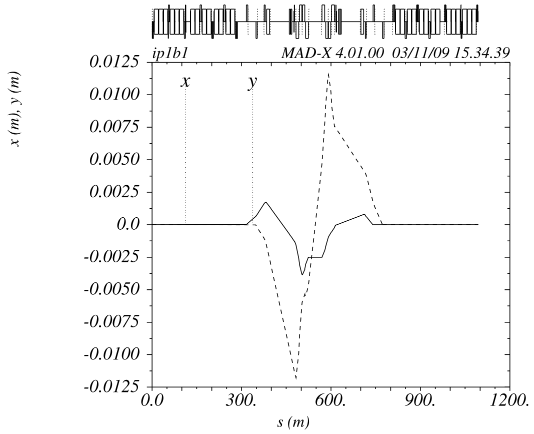
- a normalised aperture of n_1 ~6.7/7 at the defocusing/focusing quadrupoles of the dispersion suppressor which is a general feature of the nominal injection optics of the LHC (see e.g. [31]),
- a rather comfortable clearance in the matching section (except at the location of the present TAN),
- and a huge margin in the inner triplet and in the experimental beam-pipes (assuming an aperture model where the inner diameter of the central part has been reduced from 59 mm to 50 mm over ± 2 m on either side of the IP [32]).

It is worth mentioning that a certain freedom still exists in the choice of the injection optics of the new insertions. Said differently, both β^* and/or the crossing scheme might be subject to modifications in case additional criteria will have to be considered such as, for instance, the minimization of the squeeze duration. In this case, β^* would have to be further reduced at injection within certain limits imposed by the preservation of the mechanical and dynamic aperture of the machine.

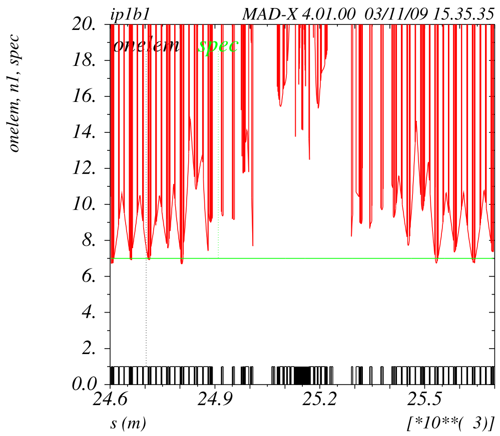
Collision. As described in detail in the previous section, severe limitations are imposed on the maximum possible peak β-function β_{max}^{IT} reached in the inner triplet (see conditions (12) and (16)). The tightest limitation, $\beta_{max}^{IT} \lesssim 11$ km, comes from the strength available in the



(a)



(b)



(c)

Figure 13: *Optics, crossing scheme and aperture plot (from Q13.L to Q13.R) for the new high-luminosity insertions of the LHC at injection ($\beta^* = 14$ m).*

lattice sextupoles (at nominal current) in order to perform a full chromatic correction of the inner triplet. Choosing $\beta^* = 30$ cm in collision is already very close to this limit since corresponding to a peak β-function of the order of 10.8 km reached the new triplet. The IT layout and slight gradient imbalances imposed on the new low-β quadrupoles (123T/m for Q1/Q2 and 122.2 T/m for Q3, see Tab. 2) have then been fine-tuned in order to minimise the co-focal length of the new triplet ($P = 312$ m as defined in Eq. 11) and therefore optimize the aperture of the matching section, leading to a β-function of less than 2 km at the entry of Q4 (see Fig. 14(a)).

As for the nominal LHC, the passage from the injection tune ($Q_{x,y} = .28/.31$) to the collision tune ($Q_{x,y} = .31/.32$) is performed at the beginning of the squeeze by applying a small shift of $\Delta Q_x = 0.015$ and $\Delta Q_y = 0.005$ to the betatron phase advances of each of the two low-β insertions IR1 and IR5. These phase advances are then kept constant during the overall squeeze in order to preserve the collision tune of the machine down to the collision β^* of 30 cm. In addtion, below a certain transition β^* ($\beta^*_{\rm trans} = 1.5$ m, see later), the left and right phase advances of the two insertions (i.e. $\Delta\mu^{\rm L/R}_{x/y}$ from Q13.L to the IP and from IP to Q13.R, respectively) are also constrained to very specific values depending on the overall optics of the rest of the ring (see next sub-section) and then kept constant till the end of the squeeze (see Tab. 2).

The full crossing angle is also fixed to $\theta_c = 410\,\mu$rad in collision ($\beta^* == 30$ cm), corresponding to a normalised value of exactly $10\,\sigma$ limited by the available aperture of the inner triplet. Before putting the two beams into collision, a full parallel separation of 1.5 mm at the IP is found to be appropriate (see Fig. 14(b)).

Under these conditions, the normalised IT aperture is $n_1 = 7.4$ assuming a standard HV or VH alternated crossing scheme in IR1 and IR5. The matching section still offers a comfortable clearance for the beam (so-called "low-P optics configuration"), but at the price that the gradients of several IR quadrupoles are very close to their limits, in particular Q7 close to 200 T/m, and Q5 and Q6 running at 20-30 T/m (see later). Then, as shown in Fig. 14(c), the only aperture bottle-neck occurs at the location of the existing TAN, when the crossing angle is chosen to be vertical.

A second collision optics is also mentioned in Tab. 2, envisaging a β^* increased up to 40 cm and a full crossing angle as large as 560 μrad, that is almost $16\,\sigma$ at $\beta^* = 40$ cm. This crossing angle corresponds to the strength limit of the MCBY orbit corrector magnets at Q4 (see condition (13)) but is still compatible with the aperture of the new triplet ($n_1 \sim 7.5$). The difference of performance between the two collision optics has been already discussed and summarized in Tab. 1. The second optics shall however not be interpreted as the one proposed for the Phase-I Upgrade of the LHC, but more as a back-up solution in case the first one would be found not flexible enough when operating the machine (since very close to the "β^{max}_{IT}-limit") and/or limited by the beam-beam effect at ultimate intensity.

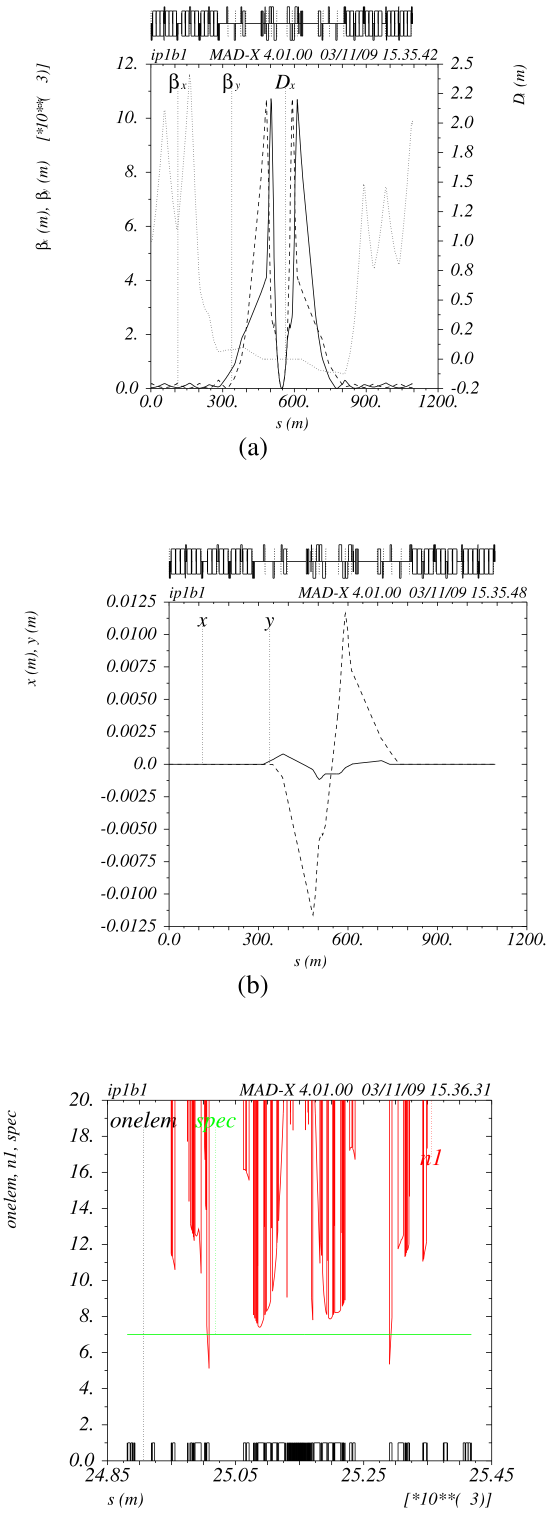


Figure 14: *Optics, crossing scheme and aperture plot (from Q7.L to Q7.R) for the new high-luminosity insertions of the LHC in collision ($\beta^* = 30$ cm). When the crossing angle is chosen to be vertical, a severe aperture bottle-neck is observed at the location of existing TAN (see Fig.(c))*

A new overall LHC optics for the chromatic correction of the new triplet

As discussed previously, a complete rephasing of the eight arcs and insertions of the LHC is required in order to correct the huge chromatic aberrations induced by the new triplets in collision (see Fig. 6). The principle proposed for this correction was indeed not known when the design of LHC optics was made and, a fortiori, when certain decisions were taken concerning the layout of the LHC insertions, such as IR4 and IR6 where the Q4 and Q6/Q7 quadrupoles, respectively, are missing. In this particular case, but also in general for all the insertions of the LHC ring, the tunability (in phase) is rather limited, essentially in the horizontal plane where the matching of the dispersion adds additional constraints which do not exist in the vertical plane. As a result, as we will see later on, optimal IR phases which would have been required for an as clean as possible chromatic correction of the inner triplet can actually not be reached and compromises are needed pushing sometimes the LHC insertions very close to their tunability limit. The main differences between the nominal LHC optics V6.503 [16] and the new overall optics SLHCV2.0 [19] are summarized in Tab. 3 and Tab. 4 and justified in detail hereafter.

Rephasing the arcs of the LHC. One of the main criteria which was used to build up the present optics of the LHC arcs was the minimization of the non-linear driving terms $c(p,q)$ potentially induced by large systematic multipole errors b_n or a_n ($n = p+q$) in the LHC main dipoles (MB), i.e.:

$$c_\pm(p,q) \sim \int_{\text{arc}} ds\; b_n(s)\beta_x(s)^{p/2}\,\beta_y(s)^{q/2}e^{ip\mu_x(s)\pm iq\mu_y(s)}$$

$$\propto N_{\text{cell}}\,\langle b_n\rangle \times \underbrace{\frac{\sin\left[N_{\text{cell}}\left(p\Delta\mu_x^{\text{cell}}\pm q\Delta\mu_y^{\text{cell}}\right)/2\right]}{N_{\text{cell}}\,\sin\left[\left(p\Delta\mu_x^{\text{cell}}\pm q\Delta\mu_y^{\text{cell}}\right)/2\right]}}_{\text{Generally} \ll 1 \text{ when } \Delta\mu_{x,y}^{\text{cell}} \neq \pi/2}, \quad (21)$$

where $\Delta\mu_{x/y}^{\text{cell}}$ represent the horizontal and vertical betatron phase advances per arc cell and $N_{\text{cell}} = 23$ the total number of cells per sector (from Q11 to Q11). A natural cure was then to adjust individually the horizontal and vertical phase advances of the arc cell on either side of $\pi/2$. This was done in practice by imposing slightly different settings for the RQF and RQD main circuits within some limits imposed by the mechanical aperture of the machine at injection and the nominal gradient of the main quadrupoles MQ ($\sim$ 220 T/m). Since the last twelve years the nominal optics of the LHC arcs has no longer been modified. This optics corresponds to the same betatron phase advances of $\Delta\mu_{x/y}^{\text{cell}} = 94.86°/87.52°$ per cell in each of the eight sectors of the machine (see Tab. 3). This gives a total phase split of about π per sector and an overall tune split of 5 (taking into account the additional $x - y$ phase split coming from the LHC insertions).

Arc cell betatron phases $\Delta\mu_x^{\rm cell}/\Delta\mu_y^{\rm cell}$ $[2\pi]$ and MQT settings	V6.503	SLHCV2.0
Sectors adjacent to the low-β insertions IR1 and IR5		
Sector 81	0.2635 / 0.2431	0.2600 / 0.2504
Sector 12	0.2635 / 0.2431	0.2598 / 0.2500
Sector 45	0.2635 / 0.2431	0.2600 / 0.2504
Sector 56	0.2635 / 0.2431	0.2598 / 0.2500
Sectors adjacent to the collimation insertions IR3 and IR7		
Sector 23	0.2635 / 0.2431	0.2531 / 0.2489
Sector 34	0.2635 / 0.2431	0.2530 / 0.2486
Sector 67	0.2635 / 0.2431	0.2541 / 0.2488
Sector 78	0.2635 / 0.2431	0.2525 / 0.2483
Tune shift quadrupole circuits RQT's		
RQTF	0	$9 \rightarrow 12$ A at 450 GeV
RQTD	0	$2 \rightarrow 3$ A at 450 GeV

Table 3: *Comparison between the nominal LHC optics V6.503 [16] and the new optics SLHCV2.0 [19] in terms of betatron phase advances per arc cell and settings of the arc tune shift quadrupoles MQT's.*

Taking into account the excellent field quality of the magnets produced, in particular for the even order multipoles such as b_4 (almost vanishing in the MB's at injection), it is therefore no longer excluded to go back to betatron phase advances of $\pi/2$ or at least closer to $\pi/2$ in the LHC arc cells. In addition, as discussed previously, imposing a $\pi/2$ phase advance in the arc cells is interesting to maximize the quality (see e.g. Eq. 17) and the efficiency of the chromatic correction of the inner triplet in collision. This requirement is particularly relevant in the vertical plane due to the fact that the defocusing sextupoles are twice less efficient than the focusing ones (simply because the dispersion function is halved at the QD's) and will therefore be limited more rapidly when reducing β^*.

Thanks to the appropriate tunability of the LHC insertions in the vertical plane, the chromatic phasing conditions, derived in detail in Ref. [18] and reminded in Fig. 6, can be achieved with vertical phase advances very close to $\pi/2$ in the LHC arc cells while preserving the fractional part of the vertical betatron tune (see Tab. 3). The LHC insertions are much less tunable in the other plane but the focusing sextupoles twice more efficient. Fulfilling the chromatic phasing conditions in the horizontal plane while preserving the fractional part of the horizontal tune basically imposes to split the LHC sectors into two categories: the four sectors adjacent to the collimation insertions (sectors 23, 34, 67 and 78) with both an horizontal and a vertical phase advance per arc cell very close to $\pi/2$ and the other four sectors, adjacent to the high luminosity insertions, where the arc cell phase advance is still of the order of 93.5° in the horizontal plane. This corresponds to a total phase split of about $\pi/2$ across these four sectors. Then, taking into account the additional $x-y$ phase split coming from the LHC insertions (see later), the new optics now corresponds to an integer tune split of 3 (compared to a tune split of 5 for the nominal LHC optics).

Finally, as shown in Tab. 3 and contrary to the nominal optics of the LHC, non-zero settings are imposed to the arc tune shift quadrupoles MQT's equipping the short-straight sections from Q14 to Q22. This is especially true for the focusing quadrupole circuits RQTF's. Without going too much into the details, the complication comes from the fact that the chromatic phasing conditions must be fulfilled simultaneously for both beams. Taking the example of the horizontal chromatic correction of the inner triplet on the left side of IP5 (see Fig. 6), one of the two phasing conditions connects the horizontal phase advance of the arc cell of sector 45, namely $\Delta\mu_x^{\rm cell45}$, to the horizontal phase advance on the left side of IR5 or, more precisely, between IP5 and the last focusing sextupole of sector 45 (located at Q12.L5 for beam1 and Q11.L5 for beam2):

$$N_{\rm cell}(\Delta\mu_x^{\rm cell45}-\pi/2)+2\,\Delta\mu_x^{\rm last\;SF\rightarrow IP5}\equiv 0\,[\pi]\ . \quad (22)$$

Then, it is worth reminding that the main quadrupole circuits act simultaneously on both beams. It is also important to know that, especially in the horizontal plane, the left and right phase advances of the high-luminosity insertions (defined from Q13.L to the IP and from the IP to Q13.R) cannot be arbitrarily tuned when the optics is squeezed. Therefore, a priori, the previous condition cannot be fulfilled individually for each beam but at least minimized for the two beams by retuning accordingly the arc cell phase advances ($\Delta\mu_x^{\rm cell45}$ in the case of Eq. 22). The LHC insertions are however conceptually defined from Q13.L to Q13.R which means that the β and dispersion functions are generally matched to the periodic structure of the LHC arcs at the exit of Q13. Extending this concept from Q22.L to Q22.R, that is using the arc tune shift quadrupole circuits with non-zero nominal settings, is then the only possibility to restore enough tunability on the left and right sides of the low-β insertions and then enable in practice the chromatic correction of each beam individually.

Modifying the optics of the LHC arcs as described hereabove may have some draw-backs to be qualified in terms of mechanical and dynamic aperture of the machine at injection. As we will see later on, the impact on the dynamic aperture (DA) at injection is at the limit of significance, with a DA of $10.2\,\sigma$ for the new optics, that is reduced by $\sim 0.5-1\sigma$ with respect to the usual values of $10.5-11\sigma$ obtained when tracking the as-built machine at 450 GeV and using the nominal optics of the LHC. Then, powering the MQT's with moderate currents, as summarized in Tab. 3, and rematching accordingly the LHC insertions from Q22.L to Q22.R, is also found to have a marginal impact in terms the mechanical aperture. In practice, reducing by a few tenths of millimeters the 4 mm aperture budget reserved for the closed orbit at injection, helps to fully recover the nominal beam clearance of the LHC arcs at 450 GeV.

Rephasing all the insertions of the LHC. The chromatic phasing conditions (see Fig. 6) have as well a direct impact on the betatron phases of the 8 insertions of the ring taking into account that, in addition, the fractional part of the betatron tunes shall be preserved and that phase advances very close to $90°$ are highly desirable in the cells of the LHC arcs. Furthermore, since both beams and the four new inner triplets shall be treated in a similar way in terms of chromatic correction, the new optics SLHCV2.0 [19] will exhibit the following symmetries.

Beam1-Beam2 IR phase split. The new optics of the LHC insertions are matched without any phase split between beam1 and beam2 contrary to the nominal optics of IR2, IR3, IR4, IR7 and IR8 (see Tab. 4).

The "trombone insertions". The insertions IR2, IR4, IR6 and IR8 have now (almost) exactly the same betatron phase advances modulo $\pi/2$, which means the same phase as far as only the off-momentum β-beating is concerned (since oscillating at twice the betatron frequency).

Within the tunability limits of these four insertions, an optimal phase advance very close to $\pi/4$ $[\pi/2]$ can actually be reached from Q13.L to Q13.R in the vertical plane (see Tab. 4). This then corresponds to a phase advance very close to $\pi/2$ $[\pi/2]$ for both beams between the last and the first defocusing sextupole on the left and right side of the insertion[7]. This configuration is indeed optimal for maximizing the coherence of the overall wave of off-momentum β-beating generated by the two sectors adjacent to IR2, IR4, IR6 or IR8, each of them being tuned with $\Delta\mu_y^{\rm cell} \approx \pi/2$ (see Tab. 3).

Similar phase advances cannot be reached in the horizontal plane. This is due to the fact that the matching of the dispersion at Q13.L/R, but also at IP2 and IP8 and, to some extent, at IP4 and IP6 as well, adds additional constraints which does not exist in the vertical plane. However, "reinforcing" the layout of IR4 and IR6 (where the Q4 and Q6/Q7 quadrupoles, respectively, are missing) or modifying the gradients of the Q4 and Q5 quadrupoles on the injection side of IR2 and IR8 (presently kept unchanged in order to preserve the matching of the transfer lines to the LHC ring), there are a priori no specific reasons why an optimal phase advance of $\pi/4$ $[\pi/2]$ could also not be reached in the horizontal plane for these four insertions.

The high luminosity insertions. As explained previously, the chromatic phasing conditions also impose rather severe constraints on the left and right phase advances of the high luminosity insertions IR1 and IR5. These constraints are only relevant when the optics is squeezed below a certain β^*, in which case the chromatic aberrations induced by the inner triplet starts to exceed certain acceptability limit and the chromatic correction via the lattice sextupoles needs to be activated (see Fig. 6). None of these conditions are currently taken into account for the nominal collision optics of IR1 and IR5 (see Tab. 4).

[7]Depending on the beam, these sextupoles are installed close to Q11.L/R or Q12.L/R due to the beam1-beam2 and left/right optics antisymmetry of the LHC insertions.

IR Phases $\Delta\mu_{x/y}^{\rm IR}$ $[2\pi]$ and betatron tunes $Q_{x/y}$	V6.503		SLHCV2.0	
	Beam1	Beam2	Beam1	Beam2
"Trombone insertions" IR2, IR4, IR6 and IR8				
$\Delta\mu_x^{\rm IR8}$	3.183	3.059	3.020	
$\Delta\mu_x^{\rm IR2}$	2.986	2.991	3.020	
$\Delta\mu_x^{\rm IR4}$	2.045	2.125	2.260	
$\Delta\mu_x^{\rm IR6}$	2.015	2.015	2.010	
$\Delta\mu_y^{\rm IR8}$	2.974	2.782	2.900	
$\Delta\mu_y^{\rm IR2}$	2.809	2.844	2.900	
$\Delta\mu_y^{\rm IR4}$	1.941	1.934	1.650	
$\Delta\mu_y^{\rm IR6}$	1.780	1.780	1.900	
Collimation insertions IR3 and IR7				
$\Delta\mu_x^{\rm IR3}$	2.261	2.260	2.255	
$\Delta\mu_x^{\rm IR7}$	2.450	2.489	2.455	
$\Delta\mu_y^{\rm IR3}$	1.905	1.990	1.955	
$\Delta\mu_y^{\rm IR7}$	1.924	2.003	1.970	
High-luminosity insertions IR1 and IR5: left, right and overall phase advances: $\Delta\mu_{x/y}^{\rm L}$, $\Delta\mu_{x/y}^{\rm R}$ and $\Delta\mu_{x/y}^{\rm Tot}$				
$\Delta\mu_{x/y}^{\rm Tot}$ (inj.)	$2.618/2.644$		$2.655/2.639$	
$\Delta\mu_{x/y}^{\rm Tot}$ (col.)	$2.633/2.649$		$2.670/2.644$	
$\Delta\mu_{x/y}^{\rm L}$ (col.)	Not specified		$1.070/1.754$	$1.605/0.890$
$\Delta\mu_{x/y}^{\rm R}$ (col.)	Not specified		$1.600/0.890$	$1.065/1.754$
Working point Q_x/Q_y				
Injection	$\mathbf{64.28/59.31}$		$\mathbf{63.28/60.31}$	
Collision	$\mathbf{64.31/59.32}$		$\mathbf{63.31/60.32}$	

Table 4: *Comparison between the nominal LHC optics V6.503 [16] and the new optics SLHCV2.0 [19] in terms of working point and phase advances (from Q13.L to Q13.R) over the 8 insertions of the machine.*

Depending on the beam, optimal horizontal and vertical phase advances of $\pi/4$ $[\pi/2]$ or $\pi/2$ $[\pi/2]$ would ideally be required from Q13.L to the IP and from the IP to Q13.R. This configuration, indeed, corresponds to phase advances close to $\pi/2$ $[\pi/2]$ in both planes between the left or right inner triplet and the first or last sextupole, focusing or defocusing, on either side of the insertion. As showed in Tab. 4, these optimal left and right IR phases can actually be reached in the vertical plane. Furthermore, these additional matching constraints are found to have only a small impact on the maximum peak β-function β_{IT}^{max} which is matchable to the LHC arcs within the IR quadrupole gradient limits and the aperture constraints of the matching section.

The situation is then quite different in the horizontal plane where the left and right phases of the insertion are basically fixed as soon as the P parameter of the inner triplet (see Eq. 11) has been chosen based on other criteria (matching section aperture, IR quadrupole gradients, see previous section). Furthermore the missing phase advance (w.r.t. to the optimal left and right IR phases) is not the same for the two beams in the horizontal plane. More precisely, on the left side of the insertion, the missing horizontal phase is $0.055 \times 2\pi$ for beam1, comparing the value of 1.07 quoted in Tab. 4 and the closest target of 1.125, i.e. $\pi/4$ $[\pi/2]$ from Q13.L to the IP, considering that Q13.L is defocusing

for beam1 in IR1 and IR5. On the other hand, this missing phase is $0.15 \times 2\pi$ for beam2, comparing the value of 1.60 quoted in Tab. 4 and a target of 1.75, i.e. $\pi/2$ $[\pi/2]$ from Q13.L to the IP, considering that Q13.L is focusing for beam2 in IR1 and IR5. The situation is then very similar on the right side of the low-β-insertion. This explains why the sectors 81, 12, 45 and 56 are tuned with an horizontal phase advance per arc cell which is substantially different from 90° (see Tab. 3) in order to compensate a missing horizontal phase advance of about $0.1 \times 2\pi$, when averaged over the two beams. Then, as already mentioned, this also explains why the trim focusing quadrupoles MQTF's, from Q14 to Q22, must be powered with a sizable current (with an opposite sign for beam1 and beam2 on a given side of the low-β insertion) in order to ensure that the chromatic phasing conditions can be fulfilled for each beam individually.
Finally, as showed in Tab. 4, it is worth noticing the almost perfect symmetry in terms of L/R phase advances specified for the two beams in IR1 and IR5:

$$\begin{cases} \Delta\mu_x^{\mathrm{L,b1}} \approx \Delta\mu_x^{\mathrm{R,b2}} \quad \text{and} \quad \Delta\mu_x^{\mathrm{R,b1}} \approx \Delta\mu_x^{\mathrm{L,b2}} \\ \Delta\mu_y^{\mathrm{L,b1}} \equiv \Delta\mu_y^{\mathrm{R,b2}} \quad \text{and} \quad \Delta\mu_y^{\mathrm{R,b1}} \equiv \Delta\mu_y^{\mathrm{L,b2}} \,. \end{cases}$$

Other considerations. It goes without saying that specific precautions have been taken when rematching the eight insertions of the LHC but additional checks are still needed to fully validate the new optics proposed (see below). In this respect the 8 insertions of the machine have been rematched according to the new optics defined in Tab. 3 for the LHC arcs and the new phase advances specified in Tab. 4, but also taken into account

- the preservation of the mechanical aperture at injection. This is granted within $\Delta n_1 \sim 0.1$ in the insertion magnets, that is a few tenths of millimeters at 450 GeV. These verifications are however still missing for the non-magnetic components of the LHC insertions such as, for instance, the empty cryostats replacing the missing dipoles close to Q11 (and the missing Q7's in IR6), the warm beam pipes of the LHC long straight sections or the warm-to-cold or cold-to-cold transitions which have been modeled very recently by inserting so-called vacuum markers into the LHC MAD sequence.

- the preservation of the functionality of the different LHC insertions. In this respect, the rephasing of the collimation insertions IR3 and IR7 has been performed by fixing the Twiss parameters at Q6 and then acting only on the dispersion suppressor quadrupoles. As a result, the new optics of IR3 and IR7 remain unperturbed in between Q6.L and Q6.R, that is in the region containing the momentum and betatron collimation systems of the LHC. Concerning IR2 and IR8 where the two beams are injected, the optics have been modified keeping unchanged the strength of the inner triplet but also, for the injected beam, the gradients of the Q4 and Q5 quadrupoles. Under these conditions, the LHC transfer lines does not need to be rematched and, in addition, the vertical phase advances between the MKI and the TDI and TCLI absorbers are kept unchanged. The dump insertion IR6 has been rematched at more or less constant Twiss parameters at the IP (in order to preserve the aperture of the extracted beam), and also fixing the gradient of the Q4 quadrupole on the MKD side (which also participates to the extraction kick and therefore has a direct impact on the geometrical positioning of the extraction septa). Finally the optics of the RF insertion IR4 have been modified taking care of preserving the size of the β-functions but also the dispersion at some key instruments and equipments of the insertion such as, of course, the RF cavities but also the transverse dampers or the tune and aperture kickers.

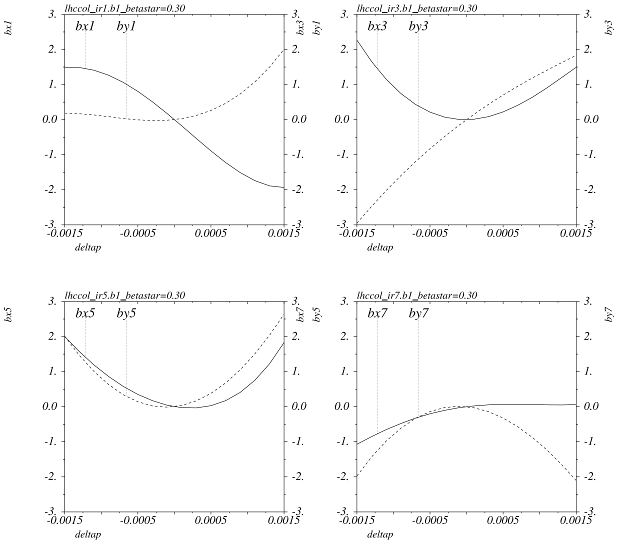
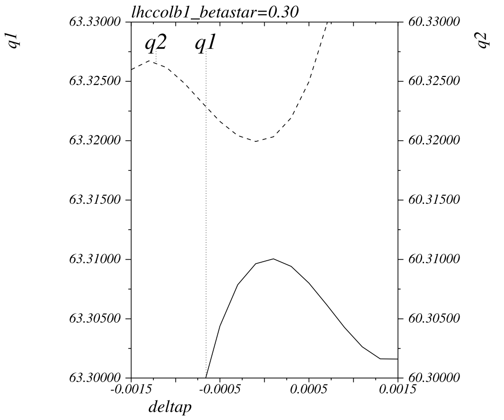


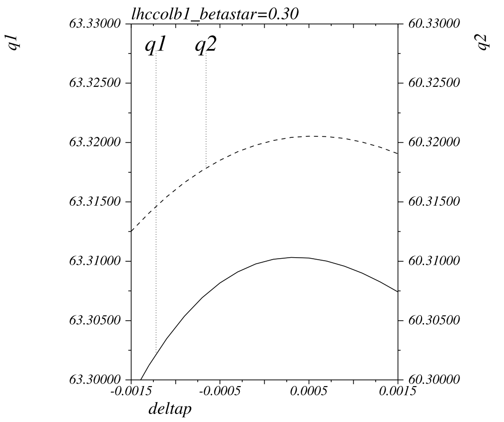
Figure 15: *SLHCV2.0 optics in collision ($\beta^* = 30$ cm. Chromatic variations of the β-functions [%] for beam1 at IP1, IP3, IP5 and IP8 after correction.*

In all cases, however, a second series of checks should be performed by the different equipment groups and the IR responsibles in order to fully validate the new optics proposed.

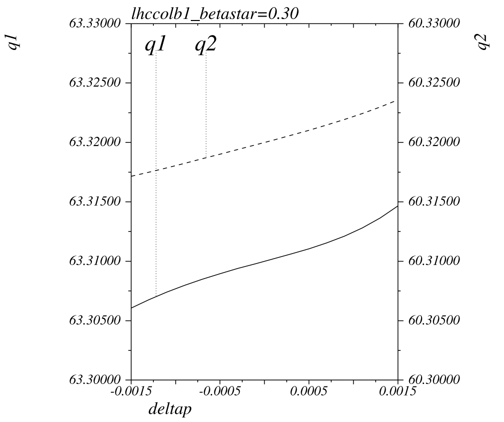
Residual Q'' as a signature of a lack of tunability in the LHC IR's. As already illustrated in Fig. 7, this new optics enable a correction of the off-momentum β-beating simultaneously in the collimation insertions IR3 and IR7 but also in the four inner triplets of IR1 and IR5. More precisely, the off-momentum β-beating after correction by the lattice sextupoles can be controlled within less than 2-3% at those critical locations up to a momentum deviation as large as 1.5 permil (see Fig. 15). The situation is not as clean concerning the non-linear chromaticity. More pre-



(a)



(b)



(c)

Figure 16: *SLHCV2.0 optics in collision ($\beta^* = 30$ cm). Chromatic variations of the betatron tunes for beam1, before any correction (a), after correction of the off-momentum beta-beating by the lattice sextupoles (b) and after fine tuning of Q'' by the lattice octupoles (c).*

cisely, as explained previously, the lack of tunability of the LHC insertions, essentially in the horizontal plane, are not compatible with a $\pi/2$ phase advance in the FODO cells of all the LHC sectors. As a result the residual second order chromaticity Q'' induced by the lattice sextupoles themselves (see Eq. 17) is not completely negligible (see Fig. 16(b)). This effect can however still be corrected, if needed, via the Landau octupole circuits ROF and ROD of the LHC arcs (see Fig. 16(c)), being noted that the currents required in the OF and OD families are then of the order of 200A and 450A, respectively.

Squeeze

Just before starting the squeeze at flat top energy, the optics of the two low β-insertions IR1 and IR5 are slowly and slightly modified in order to perform a small jump from the injection tunes (.28/.31) to the collision tunes (.31/.32). Then the reduction of β^* is achieved at constant betatron phase advances, from Q13.L to Q13.R across the low-β insertions, in order to keep unchanged the betatron tunes during the squeeze.
The LHC experimental insertions were however not designed to be "squeezable" at constant left and right phase advances individually, that is from Q13.L to the IP and from the IP to Q13.R. On the other hand, as explained previously, this functionality is one of the key ingredients for the chromatic correction of the inner triplet. Strictly speaking, these additional matching constraints are however only imposed below a certain β^* when the chromatic aberrations, in particular the off-momentum β-beating, exceeds a certain limit. Fixing this limit to

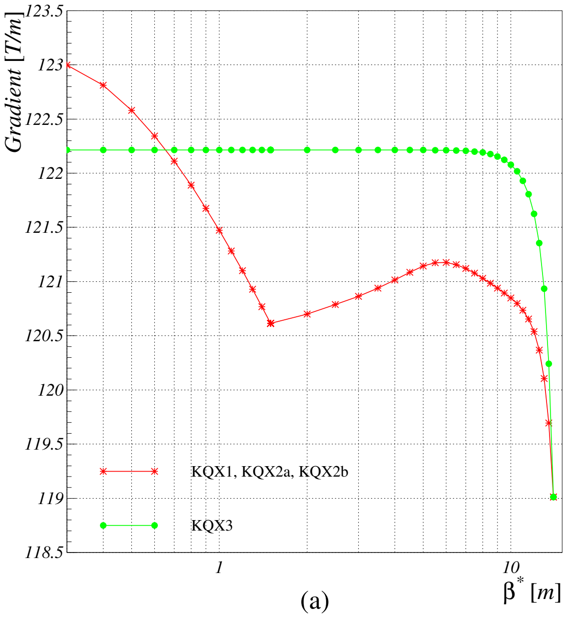
$$\left|\frac{\Delta\beta}{\beta}\right| \leq 20\% \text{ at } \delta = \pm 10^{-3}\,, \tag{23}$$

the specified left and right IR phases shall then be reached and kept constant, and the chromatic correction activated, below a transition β^* of about 1.5 m [8]:

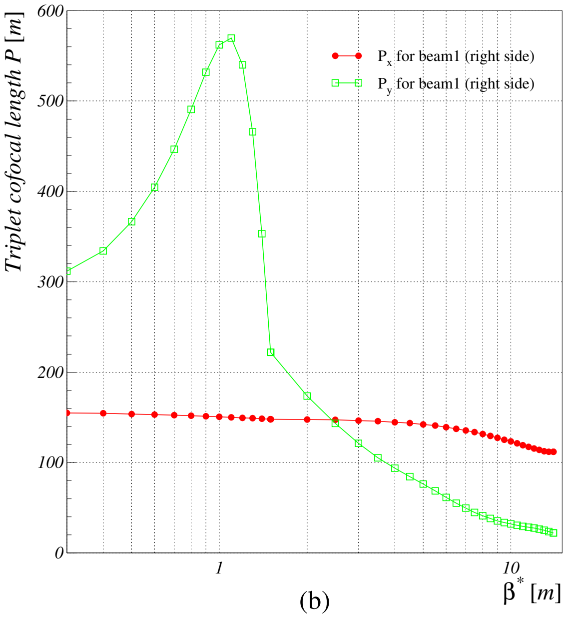
$$\beta^* \leq \beta^*_{\text{trans}} = 1.5\,\text{m} \;\Rightarrow \Delta\mu^{L/R}_{x,y} \equiv \mathbf{Cst}\,.$$

IT settings and cofocal length, and Left/Right IR phases during the squeeze. The above condition adds two additional matching constraints per beam (one per plane), at least below $\beta^* = 1.5$ m during the squeeze of the new insertions. These additional requirements go beyond the capability of the dispersion suppressors which are basically the only source of IR tunability at low β^*. A good compromise would then to also involve the trim quadrupole circuits RQTF and RQTD during the squeeze, located on either side of the each insertion from Q14 to Q22. This possibility would however add another degree of complexity due to the fact that these circuits connect in series the tune shift quadrupoles MQT on either side of a given sector. More precisely, in this configuration, the optics of the

[8]The condition (23) is already twice more demanding than the uncorrected 40% off-momentum β-beating actually reached with the nominal collision optics of the LHC.



(a)



(b)

Figure 17: *Low-β quadrupole gradients [T/m] (top) and horizontal and vertical cofocal lengths $P_{x,y}$ [m] of the new triplet (bottom) as a function of β^*[m] (logarithmic scale). The IT parameters $P_{x,y}$ are defined in Eq. 11 and are plotted hereabove for beam1 and for the right triplet. Using this convention, the P parameter of the inner triplet, impacting directly on the mechanical acceptance of the matching section, corresponds to P_y. It is almost doubled when "unsqueezing" the optics from $\beta^* = 30$ cm to $\beta^* = 1.5$ m at non-constant triplet settings but constant left and right phase advances from Q13.L to the IP and from the IP to Q13.R.*

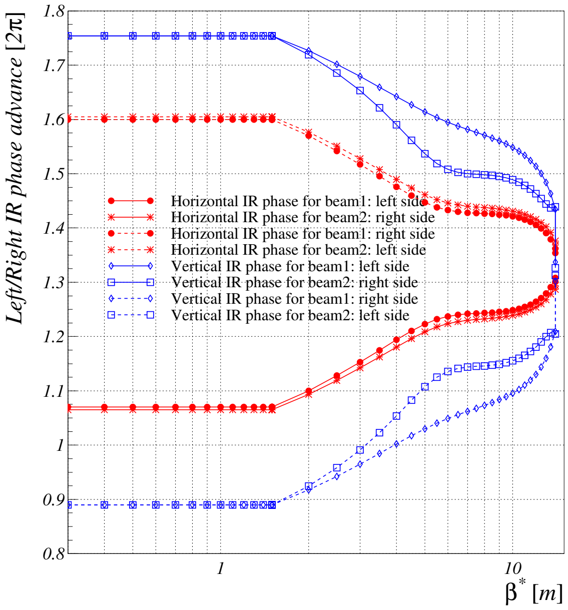
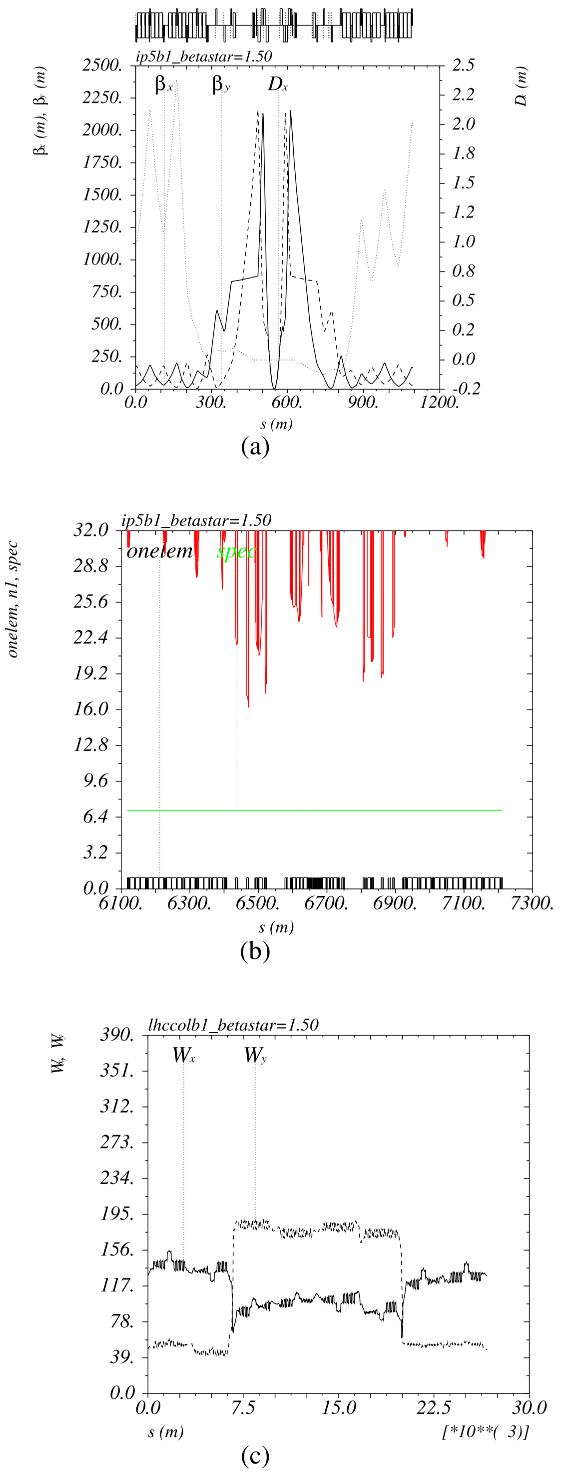


Figure 18: *Left and right phase advances of the new insertion (from Q13.L to the IP and from the IP to Q13.R) for beam1 and beam2 as a function of β^*. Just after the phase jump to go from the injection tunes to the collision tunes, the squeeze is performed at constant phase advances across the overall insertion (from Q13.L to Q13.R). The left and right IR phases are then kept constant individually below the transition β^* of 1.5 m.*

insertions IR8, IR2, IR4 and IR6 would then be intrinsically coupled to the squeeze of the low-β insertions IR1 and IR5. The only solution found is then to modify the settings of the inner triplet itself (within a few T/m) in a non-monotonous way during the squeeze and with a clear transition at $\beta^* = \beta^*_{\mathrm{trans}} = 1.5$ m (see Fig. 17(a)). As shown in Fig. 17(b), this strategy has a clear impact on the co-focal length of the new triplet (parameter P, see Eq. 11) during the last part of the squeeze. Indeed this parameter would be otherwise more or less constant at low β^* as it is the case for the nominal squeeze of the present insertions IR1 and IR5 when the IT gradient is no longer modified below $\beta^* = 2$ m.

Within the constraints of the existing arcs and dispersion suppressors of the LHC, this strategy is then the only one found suitable in order to keep constant individually the left and right phase advances of the high-luminosity insertions during the last part of the squeeze (see Fig. 18). More precisely, starting from the collision optics with $\beta^* = 30$ cm, it is found that the P parameter of the inner triplet has to be increased in order to "unsqueeze" the insertion at constant left and right phase advance up to the transition β^* of 1.5 m. As previously explained and clearly illustrated in Fig. 19, the normalised aperture of the matching section can then be lower than that of the low-β quadrupoles when the P parameter of the inner triplet is not sufficiently minimized.



(a)

(b)

(c)

Figure 19: *Optics (a) and corresponding normalised aperture from Q13.L to Q13.R (b) for the new insertion at the transition β^* of 1.5 m where the chromatic correction starts to be activated. The bottom figure shows the off-momentum β-beating envelop around the LHC ring (starting from IP3) just before activating the chromatic correction of the inner triplet: $W_{x,y} = 200$ is equivalent to a peak off-momentum β-beating of 20% at $\delta = \pm 10^{-3}$.*

This feature, occurring only at intermediate β^* (and down to $\beta^* \approx 60$ cm) will then have to be kept in mind when the settings of the collimator jaws will have to be defined during the squeeze of the new insertion.

Evolution of the IR quadrupole gradients during the squeeze. The settings of the IR quadrupoles as a function of β^* are showed in Fig's 20(a) to 20(c), concerning the matching section quadrupoles (Q4, Q5 and Q6), the dispersion suppressor quadrupoles (from Q7 to Q10) and the trim quadrupoles (from Q11 to Q13), respectively. The transition at $\beta = \beta^*_{\text{trans}} = 1.5$ m is clearly visible while the evolution of the IR quadrupole settings is rather smooth on either side of the transition. It is worth noting that the Q5 and Q6 quadrupoles reach rather low gradients at $\beta^* = 30$ cm while Q7 approaches dangerously its nominal gradient of 200 T/m. At low β^* some standalone tune shift quadrupoles (QT12 and QT13 on the right and left side of the insertion for beam1 and beam2, respectively) must be operated with a current which is very close to nominal (550A). Finally, within the nominal gradient limits of the IR quadrupoles, it is worth mentioning that a matched optics solution can no longer be found below a β^* of about 28 cm.

Evolution of the sextupole and octupole strengths during the squeeze. The squeeze of the new insertions will then be done in three well-identified steps:

- **Step 1.** During the first step, β^* is reduced down to $\beta^*_{\text{trans}} = 1.5$ m, at constant phase advance from Q13.L to Q13.R (after the initial phase jump described previously). During this process the focusing (resp. defocusing) sextupole circuits are powered with the same current for correcting the horizontal (resp. vertical) linear chromaticity of the machine. The Landau octupoles does not need a priori to be powered.

- **Step 2.** At $\beta^* = 1.5$ m, the specified left and right phase advance of the insertion can be reached (see Fig 18). The squeeze of the insertion is then interrupted and the up and down excitation scheme of the lattice sextupoles (see Fig. 6) is activated in order to compensate the off-momentum β-beating already visible at $\beta^* = 1.5$ m (20% at $\delta = 10^{-3}$, see Fig. 19(c)). If needed, the OF and OD octupole families can also be powered for fine correction of the residual second order chromaticity Q'' induced by the sextupole themselves (see Eq. 17).

- **Step 3.** The squeeze of the optics is restarted and continues down to the collision β^* of 30 cm, keeping constant individually the left and right phase advances of the insertion. For each matched optics in between $\beta^* = 30$ cm and $\beta^* = 1.5$ m, the settings of the different sextupole circuits are adjusted in order to correct both the linear chromaticity and the chromatic aberrations induced by the inner triplets. The residual Q''

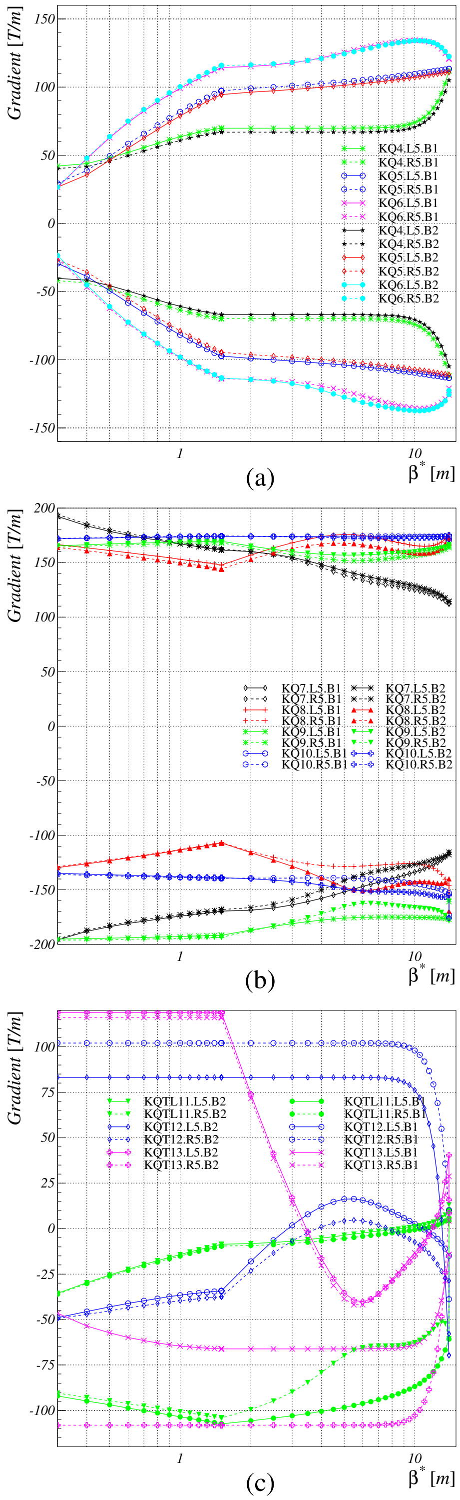


Figure 20: *Evolution of IR quadrupole gradients [T/m] during the squeeze: the matching section quadrupoles Q4, Q5 and Q6 ($G_{\mathrm{nom.}} = 160$ T/m), the dispersion suppressor quadrupoles from Q7 to Q10 ($G_{\mathrm{nom.}} = 200$ T/m) and the standalone quadrupoles MQTL and MQT equipping Q11 to Q13 ($G_{\mathrm{nom.}} = 120 - 125$ T/m) are showed in Fig(a), Fig.(b) and Fig.(c), respectively.*

can eventually be fine tuned, if needed, by the lattice octupoles.

The settings of the 64 LHC sextupole families (2 per plane, per sector and per beam) are showed in Fig. 21 as a function of β^*. When β^* approaches 30 cm, half of the defocusing sextupole families must be powered with a current very close to nominal (550A corresponding to an normalised strength of $K_{\max} = 0.38\,\mathrm{m}^{-3}$ at 7 TeV). A possible usage of the Landau octupole families during the squeeze is also illustrated in Fig. 21(c) in case a perfect compensation of the residual Q'' would also be needed.

Dynamic aperture

This last sub-section will give a summary of the tracking results obtained at injection and in collision, including or not the beam-beam effect, and using the new optics and layout SLHCV2.0 [19]. The three following configurations will be presented and discussed:

- **Case 1.** New Injection optics at 450 GeV with $\beta^* = 14/10/14/10$ m in IR1, IR2, IR5 and IR8, respectively.
- **Case 2.** New Collision optics at 7 TeV with $\beta^* = 0.3/10/0.3/10$ m in IR1, IR2, IR5 and IR8 and a vertical and horizontal normalised crossing angle of $10\,\sigma$ ($\theta_c = 410\,\mu$rad) in IR1 and IR5, respectively.
- **Case 3.** Idem except an increase of β^* up to 40 cm in the high luminosity insertions which, combined with a full crossing angle increased up to 560 μrad ($\sim 16\,\sigma$ at $\beta^* = 40$ cm) still warrants enough beam clearance in the inner triplet ($n_1 \sim 7$).

Each of these cases has then been sub-divided into the following sub-cases:

- **Sub-Case 1.** No beam-beam effect but multipole field errors assigned to all the magnets of the ring, based on the magnetic measurements for most of the magnets except, of course, for the new triplets and separation dipoles D1 in IR1 and IR5 for which the usual statistical error assignment procedure is applied. The error tables used for the new triplet and D1 at injection coincide with the expected ones and found in Ref.'s [22] and [23], respectively. In collision, the error table target10 [26] is used for D1 and specific targets have been assumed for the low order multipoles of the inner triplet ($n \leq 6$) using the formula given in Eq. 19. Sixty different machines (seeds) are then generated accordingly. Finally, as discussed previously, the new inner triplet is assumed to be equipped with the same set of non-linear correctors as the one implemented in the existing triplet.
- **Sub-Case 2.** Idem but with head-on and long-range beam-beam interactions, assuming in particular 21 parasitic beam-beam encounters on either side of IP1

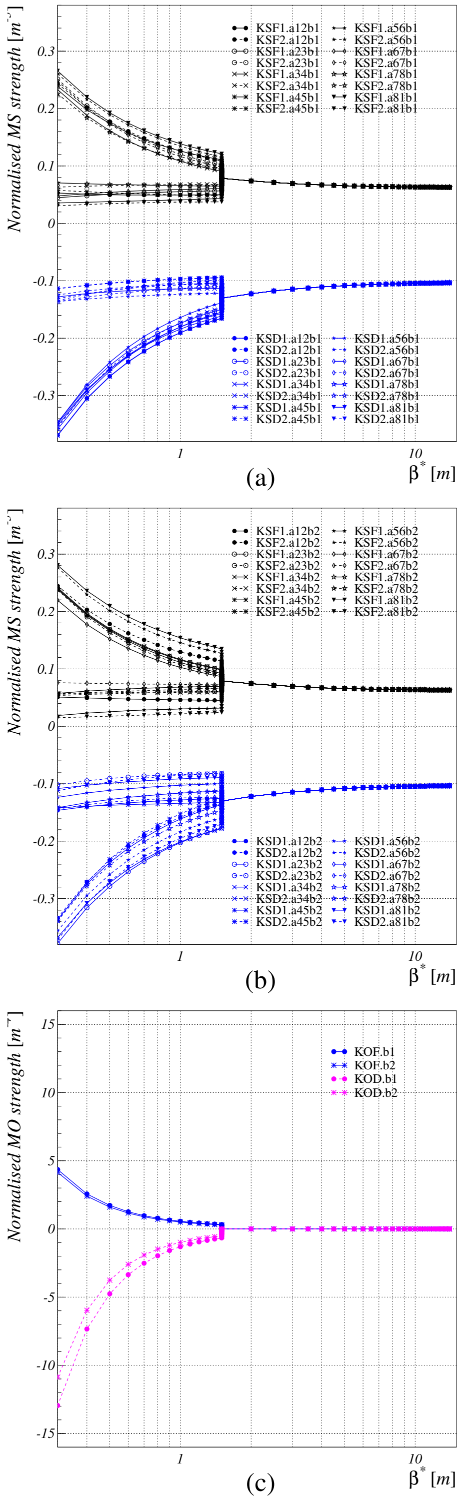


Figure 21: *Normalised strength $[m^{-3}]$ of the 64 LHC sextupole families as a function of β^* for beam1 (a) and beam2 (b). Possible non zero settings imposed to the Landau octupoles for the fine tuning of Q'' during the squeeze are illustrated in Fig.(c). The nominal current of 550 A corresponds to a maximum normalised strength of $K_{2,\max} = 0.38\, m^{-3}$ and $K_{3,\max} = 16.2\, m^{-4}$ for the lattice sextupoles and octupoles of the LHC.*

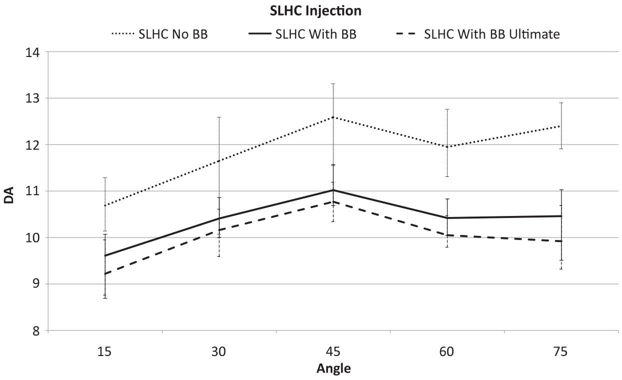
and IP5 up to D1. For completeness, five additional parasitic encounters are added beyond the magnetic entry of the 8 D1 separation dipoles which equip the four LHC experimental insertions, till the beam-beam separation is larger than 50 mm. Halo collision is only assumed in IR2, in particular beams are colliding head-on in IP8. The head-on collisions are simulated by installing five beam-beam lenses around IP1, IP5 and IP8. For the time being, these lenses are still four-dimensional which means that the possible excitation of synchrotron-betatron resonances by the crossing angle is not taken into account in the simulations. The beam intensity is assumed to be nominal (i.e. 25 ns bunch spacing with $N_b = 1.15 \times 10^{11}$ p/bunch).

- **Sub-Case 3.** Idem but assuming the ultimate intensity (i.e. 25 ns bunch spacing with $N_b = 1.70 \times 10^{11}$ p/bunch).

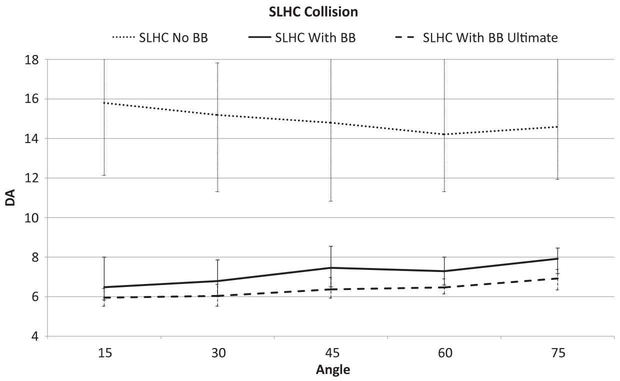
The results obtained are showed in Fig.'s 22(a), (b) and (c).

Injection. The field imperfections of the LHC main dipoles represent the main contribution to the machine non-linearities at injection. Any modification of the optics in the LHC arcs, in particular pushing as much as possible the arc cell phase advances towards $\pi/2$, may therefore be detrimental to the dynamic aperture (DA) of the machine at 450 GeV (see e.g. Eq. 21). The reduction of the integer tune split for 5 to 3 in the new optics SLHCV2.0 [19] is however found to have a minor impact on the DA at injection energy. As shown in Fig. 22(a), the dynamic aperture of the machine is still slightly larger than 10σ for the worst seed without beam-beam effect, compared to typical values of the order of $10.5 - 11\sigma$ obtained with the nominal injection optics.
Then, taking into account the long-range beam-beam interactions at injection, the dynamic aperture drops down by about $1.5-2\sigma$ but is still above $\mathrm{DA}_{\min} \sim 8.5\,\sigma$ in the worst case (ultimate intensity, horizontal plane, worst seed), that is above the betatron extension of the secondary halo. In that respect, there is no clear sign of possible intensity limitation induced by the beam-beam effect at injection, at least up to the ultimate intensity of the LHC beam,

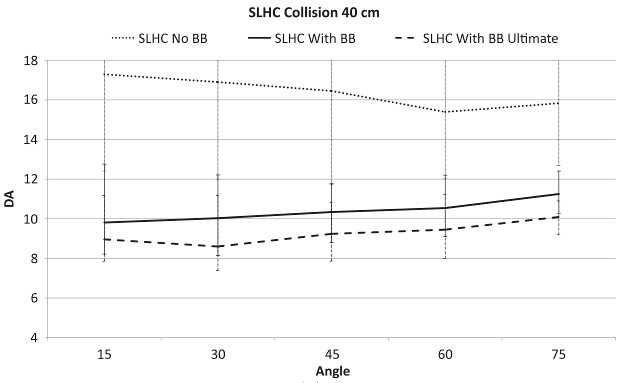
Collision. The situation is then quite different in collision where the machine non-linearities are dominated by the field imperfections of the new inner triplets and superconducting D1's. As discussed previously the field quality of these new magnets shall be further optimized in order to meet a target design dynamic aperture of the order of $11 - 12\sigma$ in collision, without beam-beam effects.
The beam-beam induced tune spread, when combined with the long-range beam-beam interactions and the non-linear field imperfections of the machine, has then a major impact on the dynamic aperture. In this configuration, a minimum/maximum DA (depending on the seed number) of the



(a)



(b)



(c)

Figure 22: *1'000'000 turns average and min/max (error bars) dynamic aperture* $[\sigma]$ *as a function of the phase space angle* $[^\circ]$*, obtained for 60 different seeds at injection (top) and at 7 TeV assuming two different possible collision optics for IR1 and IR5 (fig.'s (b) and (c)): (*$\beta^* = 30$ *cm,* $\theta_c = 410\,\mu rad$*) and (*$\beta^* = 40$ *cm,* $\theta_c = 560\,\mu rad$*), both optics corresponding to the same normalised aperture in the new triplet (*$n_1 = 7.4$*). For each of the three cases, simulations have been performed at zero intensity (i.e. no beam-beam effect in dotted lines, with expected / improved field quality for the new IT and D1 at 450 GeV / 7 TeV) or assuming the nominal (solid lines) or ultimate (dashed lines) beam intensity. Courtesy of E. Laface.*

order of $5.5/6.5\,\sigma$ is obtained at ultimate intensity, concerning the collision optics with $\beta^* = 30$ cm and a full crossing angle of $\theta_c = 10\,\sigma$ (see Fig. 22(b)). Then, it is worst mentioning that an even worst dynamic aperture of the order of $4.5\,\sigma$ is actually reached when limiting the chromatic correction of the inner triplet to the only compensation of the linear chromaticity.
Comparing with the nominal machine (for which a complete compensation of the chromatic aberrations is not available but the field quality of the inner triplet is strongly optimized), a very similar dynamic aperture of the order of 6σ is also obtained, which represents one of the well-known limitations of the present LHC in collision.

In that respect and as already mentioned, the design of the new triplet, corrector package and separation dipole shall be made very compact in order to limit as much as possible the number of parasitic beam-beam encounters on either side of the IP. Then a robust back up collision optics needs also to be worked out for Phase I, with a more or less increased β^* which would restore enough aperture margin in the inner triplet in order to accommodate a normalised crossing angle larger than 10σ. An extreme case can then be obtained by working at the limit of strength for the MCBY orbit correctors at Q4, which corresponds to a maximum full crossing angle of $560\,\mu$rad (see Eq. 13). Under these conditions, β^* has to be relaxed to 40 cm in order to restore enough clearance in the inner triplet ($n_1 \sim 7$). When the beam-beam effect is not included at larger crossing angle, the improvement of the dynamic aperture is rather limited of the order of $\sim 1\,\sigma$ for the minimum DA by comparing the cases showed in dotted lines in Fig.'s 22(b) and 22(c) (while an improvement of the DA by 15%, i.e. 2σ, is expected at constant crossing angle when relaxing β^* by 30%). The benefit is then clearly visible in the presence of beam-beam effects where a dynamic aperture ranging in between $7.5\,\sigma$ and 11σ (depending on the seed considered and therefore on the triplet and D1 field quality) can be reached at ultimate intensity (see case illustrated in dashed line in Fig. 22(c)).

As shown in Tab. 1 and already discussed, this extreme configuration with a normalised crossing angle of almost $16\,\sigma$ at $\beta^* = 40$ cm is at priori quite costly in terms of peak luminosity (50% reduction on paper compared to the $\beta^* = 30$ cm optics). However, in the case where the intensity of the LHC beam would be severely limited by the beam-beam effect, it is not at all excluded that this back up optics, or any intermediate optics preserving the triplet aperture (e.g. with $\beta^* = 35$ cm and $\theta_c = 13\,\sigma \approx 0.5$ mrad), will be the only way to reliably operate the machine at ultimate intensity and therefore optimize in practice the integrated luminosity of the LHC.

SUMMARY AND REFLEXION FOR PHASE II

The LHC insertions upgrade phase I was initially motivated by the possibility to increase the machine performance by a substantial reduction of β^* while still leaving a certain aperture margin in the inner triplet (e.g. $\beta^* = 25$ cm with 3σ margin per beam [3]) in order to mitigate any possible intensity related limitations when pushing the beam up to the ultimate intensity (emittance growth, collimator impedance requiring a larger than expected normalised IT aperture in order to open the gap of the collimator jaws, long-range beam-beam interactions requiring a larger than expected crossing angle). Most of the efforts then naturally converged towards the first limitation which is the aperture of the inner triplet and a robust principle was drawn accordingly: long enough, weak enough low-β quadrupoles can in principle offer more aperture than actually needed by the beam, at any given β^* and regardless of the choice of the technology chosen for the inner triplet.

Any other limitations possibly hidden by the first one were however put aside (e.g. matching section aperture) and other conceptual ingredients were not included in the analysis, such as the correction of the chromatic aberrations (i.e. not only Q' but also the off momentum β-beating and the non-linear chromaticity). Although of different nature, each of these limitations can generally be quantified by imposing a limit on one single quantity, the peak β-function β_{IT}^{max} reached in the inner triplet, regardless of the characteristics of the triplet itself in terms of layout (to some extent), operating gradient and technology.
For the current layout of the LHC ring (excluding the triplet) and nominal strength limits of the LHC magnets, the following β_{IT}^{max} limits shall be kept in mind and compared with the actual peak β-function of 4.4 km reached for $\beta^* = 55$ cm in the 205 T/m existing triplet:

- **Correction of the linear chromaticity:** $\beta_{IT}^{max} \lesssim$ 17 km depending on the beam energy and on the optics of the LHC arcs (dispersion and β-functions), and assuming a maximum current of 550A in the defocusing sextupoles of the lattice.
- **IR quadrupole limits:** $\beta_{IT}^{max} \lesssim$ 16 km, assuming the nominal and quite large cofocal length of the existing triplet with $P \sim 1$ km and independent on the beam energy since the matching section quadrupoles Q5 and Q6 goes to extremely low field while other quadrupoles of the dispersion suppressor reach their nominal gradient (Q7 and some MQT's at Q12 and Q13).
- **Matching section aperture:** in between $\beta_{IT}^{max} \lesssim$ 9 km for high-P triplet layout, with substantial margins for the IR quadrupole gradients (compare with the limit above), possibly increased up to $\beta_{IT}^{max} \lesssim$ 13 km for low-P triplet layout with no margin on the IR quadrupole gradients, i.e. no optics flexibility (compare e.g. Fig.'s 3 and 4). These limits stands for the nominal physical emittance of the beam at 7 TeV, for a normalised crossing angle of $10\,\sigma$ and following the standard prescription of $n_1 = 7$ for the normalised aperture of the LHC cold magnets [2].
- **IR tunability in terms of left/right phase advance:** $\beta_{IT}^{max} \lesssim$ 12 km in order to reach optimal betatron vertical phase advances on the left and right side of the high luminosity insertions in view of the full chromatic correction of the inner triplet (see below).
- **Correction of the chromatic aberrations:** $\beta_{IT}^{max} \lesssim$ 11 km, only dependent on the beam energy assuming a maximum current of 550A in the defocusing sextupoles, and also and mainly requesting already a global modification of the LHC optics.

Only the first limit, that is the less stringent one related to the correction of the linear chromaticity, was generally addressed, but corresponding to a minimum β^* still far below the target of Phase-I (see e.g. [33]).
In particular, overcoming the third limit related to the aperture of the matching section is not included in the mandate of the Phase I project. This therefore imposes a triplet layout with an as short as possible cofocal length (parameter P) paying the price of a quite poor optics flexibility (IR quadrupole gradients close to the limits at $\beta^* = 30$ cm).
Finally the most stringent limit ($\beta_{IT}^{max} \lesssim 11$ km) was only established very recently when a clear strategy was found for the correction of the chromatic aberrations [18].

Nevertheless, optics solutions down to $\beta^* = 30$ cm are still accessible to the Nb-Ti technology but with no aperture margin in the corresponding 120 mm-120 T/m triplet and leaving only little margin if no margin at all w.r.t. to the limitations coming from the rest of the ring ($\beta_{IT}^{max} = 10.8$ km reached in the new triplet). In particular such proposal is at the limit for a full correction of the chromatic aberrations, and put the low-β insertions very close to the matchability limit with a low-P optics configuration imposed by the optimization of the beam clearance in the matching section.

Several possible measures have then been suggested in this paper to mitigate if not overcome the β_{IT}^{max} limits mentioned above, but also to reestablish a substantial aperture margin in the 120 mm - 120 T/m triplet which is presently proposed. These measures, summarized below for Phase-I, shall not be understood as suitable solutions for a further reduction of β^*, but as possible directions in order to restore enough margins and optics flexibility on the non-triplet side and therefore maximize the probability of a reliable operation of the machine at a β^* of 30 cm.

- **Flexibility of the optics in the low-β insertions, and matching section aperture.** Recommission the dispersion suppressor quadrupoles, in particular Q7 (MQM type magnets at 1.9K), at ultimate current (6 kA, corresponding to a gradient of 220 T/m, as already tested in SM18 [34]), and/or readjust the layout of the matching section to the length of the new triplet (basically pushing the D2/Q4 and the Q5 assemblies by 15 m and 10 m, respectively, towards the arc), and/or (re-)optimize the beam-screen orientation in the D2, Q4 and Q5 magnets, and/or provide larger aperture MQY-type magnets to replace Q5 (MQM-type). All these measures aim to re-increase the cofocal length (parameter P) of the Phase-I triplet, ideally from 300 m to about 1 km as for the nominal collision optics, while preserving enough beam clearance in the matching section and finding optics solution well within the gradient limits of the IR quadrupoles. Presently, it is indeed not granted that the Phase-I collision optics with $\beta^* = 30$ cm could be readjusted in operation, assuming a β-beating wave larger than 5-10% leaking from the LHC arcs.

- **IR tunability in phase.** Re-cable into two families the tune shift quadrupoles MQTF(D) which are presently powered in series on either side of each sector of the LHC ring (one family per plane and per beam from Q14 to Q22). From the optics point of view, the principle is to redefine the LHC insertions from Q22.L to Q22.R, that is embracing the arc tune shift quadrupoles. As a result, enough tunability in phase will be restored in the insertions of the LHC and, in particular, for the left and right phase advances of the low-β insertions where new matching constraints are imposed at low β^* by the correction of the chromatic aberrations. In parallel, the squeeze sequence of the new IR will be much less complex than the one presently proposed and then shorter (see previous discussion), which also means a beneficial impact on the turn around time and therefore on the integrated luminosity.

- **Sextupole strength.** Recommission the lattice sextupoles up to the ultimate current (600 A as already achieved for most of the MSCB correctors in SM18 [34]) in order to gain margin for the chromatic correction of the inner triplets at $\beta^* = 30$ cm. This margin will certainly be needed in the presence of linear imperfections and betatron phase errors randomly distributed in the LHC ring.

- **Crossing angle.** Install additional orbit corrector magnets to reinforce the MCBY dipole correctors at Q4 in IR1 and IR5 and leave enough provision for Vernier scans and IP steering when operating the machine with a crossing angle as large as ~ 0.5 mrad.

Finally, the new inner triplet itself should still be optimized for several aspects.

- **Effective aperture.** Reduce as much as possible the fraction of aperture needed to accommodate the cold bore and beam-screen (basically the difference between the coil and beam-screen inner diameters estimated to 21 mm for the new triplet), starting by improving as much as possible the manufacturing tolerances of the new cold bore.

- **Layout.** Optimize the compactness of the layout till D1, in order to reduce as much as possible the number of parasitic beam-beam encounters on either side of the IP (triplet service module installed on the non-IP side of D1 and/or corrector package and D1 compacted in the same cryo-assembly).

- **Corrector.** Equip the new triplet with as short as possible double plane orbit correctors and reserve enough room in the corrector package to accommodate nested non-linear correctors as in the existing triplet.

- **Field quality.** Further optimize the field quality of the new triplet and mainly of the new D1 compared to the present expectations [26].

In order to complete this summary, it is obviously relevant to draw some conclusions for any upgrade phase of the LHC. As soon as the aperture budget needed for the beam is known, and taking into account the present limits imposed by the LHC ring for the correction of the chromatic aberrations, an optimum aperture for the new triplet can be fully determined (see Eq. 8) regardless of the IT technology, of the IT gradient and, to some extent, of the layout of the new interaction region. More precisely, assuming the nominal aperture budget for the LHC beam in terms of emittance, normalised crossing angle and opening of the collimator jaws (which is a fundamental assumption and will have to be assessed when gaining experience running the LHC), and taking into account the most stringent ring limit of 11 km imposed on β_{IT}^{max}, an optimal 100 mm clearance has been found for any new inner triplet. This 100 mm clearance shall be understood as the inner dimension of the triplet beam-screen. Below 100 mm, the minimum possible β^* is limited by the triplet aperture. Beyond 100 mm, the minimum possible β^* is limited by the rest of the machine (correction of the chromatic aberrations, IR optics flexibility) and the unnecessarily low IT gradient (i.e. the extra IT aperture can simply not be used by the beam).
Then, only after having determined this optimum aperture, the choice of the IT technology plays a role, impacting on the IT operating gradient and finally on the minimum possible β^*. This minimum β^* is then directly given by the β_{IT}^{max} limit imposed by the rest of the machine and by (almost) nothing else. More precisely, its scaling is rather moderate with respect to the IT technology, with the square root of the critical field, as showed in Eq. 8 and already observed in [35] when comparison between the Nb-Ti and Nb3Sn technologies were investigated at constant linear chromaticity. Actually the impact of the technology is much more relevant in terms of magnet length (basically inversely proportional to the critical field when the optimum IT aperture has been chosen). However, unless the aperture budget foreseen for the LHC beam has been severely under-estimated, and taking into account the very stringent current chromatic limit of the LHC ring, the triplet length limit remains relatively faraway in the case of the LHC. In that respect, pending a very inspired idea to significantly relax the β_{IT}^{max}-limit imposed by the correction of the chromatic aberrations at the 7 TeV design energy of the ring (and without forgetting the matching section aperture limit

which is just behind), a change of the triplet technology is a priori not justified at this stage for the Phase II upgrade: that is to really gain in β^*_{min} with (at most) the square of the critical field as derived in Eq. 5.

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