Breaching the Phase I Optics Limitations for the HL-LHC

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Abstract

This paper scrutinizes the performance goal of the HL-LHC Project and proposes a solution to reach it. This solution is based on an Achromatic Telescopic Squeezing (ATS) principle which can push β^* well below the limits which were identified in the context of the so-called Phase I Upgrade studies. The novel optics scheme is described, with its main weak points, possible mitigation measures and hardware modifications needed in the LHC ring in order to implement it. Other implications or by-products are also highlighted. Some of them are rather exotic and are worth to be mentioned in the abstract even if not completely developed in the paper: the possibility to run with a third low-β experiment installed in IR3 or IR7 (which is an interesting direction for a smooth co-habitation between the HL-LHC and the LHeC), a notable reduction of the IBS growth rate in the longitudinal plane (generally the most critical plane), or a boost by more than one order of magnitude for the efficiency of the Landau octupoles, making them strong enough to shape the head-on beam-beam tune footprint (but without yet any demonstration of the possible benefits) or, at least, to relax the constraints on the transverse impedance budget of the LHC at 7 TeV.

INTRODUCTION

One key ingredient to push the performance of a collider is a reduction of the transverse beam sizes at the interaction point (IP), which are directly given by the transverse emittances of the beam and by the value of the β-functions at the IP, i.e. β^*_x and β^*_y. Intrinsic limitations obviously exist for each of these quantities, driven by the performance of the injector for the first one and by a series of optics and aperture related constraints for β^* in the LHC.

Using the usual concept of a circular collider where low-β insertions (IR) with "squeezable" optics are interleaved with passive arcs used to transport the beam at constant optics, and counting already on a very sophisticated scheme for the correction of the chromatic aberrations induced by the final quadrupoles of the experimental IR's [1], the limit on β^* was clearly identified for the LHC (see [2] and reference therein). This limit was found to be in the range of $\beta^* \approx 30$ cm for an inner triplet (IT) based on the NbTi technology, possibly reduced to $\beta^* \approx 24$ cm (i.e. $\sim 25\%$ gain) assuming the availability of Nb3Sn quadrupoles at the horizon of the LHC Upgrade. Those two numbers did not include any provision for operational margins and were driven by the chromatic correct-ability of the new triplet within the nominal strength budget of the lattice sextupoles (with two sectors of sextupoles needed for the chromatic correction of one single triplet, and an extremely rigid overall optics due to a series of phase advance constraints imposed all around the machine). In addition other limitations were also analysed, related to the mechanical acceptance of the existing matching section and to the optics flexibility of the low-β insertions, and found just in the shadow of the above limit. In view of these severe limitations and following the decision to cancel the Phase I project and to combine it with a single Upgrade project at the horizon 2020-2021, the so-called HL-LHC project, a novel optics concept was then mandatory in order to satisfy the very ambitious performance target of this new project.

The HL-LHC performance target will be discussed in the next section and the potential of flat collision optics (i.e. with a β^* aspect ratio different from unity) will be introduced at this occasion. Then will follow a short reminder of the Phase I optics limitations and a brief description of the new optics scheme in order to breach them (see [3] for more details). The latter is based on a "Achromatic Telescopic Squeezing" (ATS) principle as we will understand it a bit latter. The main weak points of the ATS scheme will then be presented, with possible mitigation measures and the hardware changes needed in the LHC ring in order to implement it. Finally in order to demonstrate the powerfulness of the novel approach, the ATS scheme will be used in order to propose and analyze a complete solution for the Upgrade of the LHC, even in a worst case where the crab-cavity technology would not be available on time for the HL-LHC. In this scenario, the crossing angle seems then to be the most promising tool for luminosity leveling (see e.g. [4]), which is one of the keystones of the new project. This alternative has however the reputation of being very demanding in terms of triplet aperture (except in the case of the so-called "early separation scheme" which assumes the installation of orbit corrector inside the detector [5]). We will see that this is not really the case for a flat collision optics where the crossing angle is chosen in the plane of largest β^*.

PERFORMANCE TARGET OF THE HL-LHC

The performance goal of the HL-LHC is to integrate a luminosity of 3000 fb^{-1} over the full life time of the machine (see e.g. [6]), that is typically 25 years for a large hadron machine taking as (unique) example the Tevatron. Then counting on an unique upgrade of the machine at the horizon of 2020-2021, followed by a few years to recommission the machine and ramp it up to its maximum performance, the above target corresponds to an integrated lu-

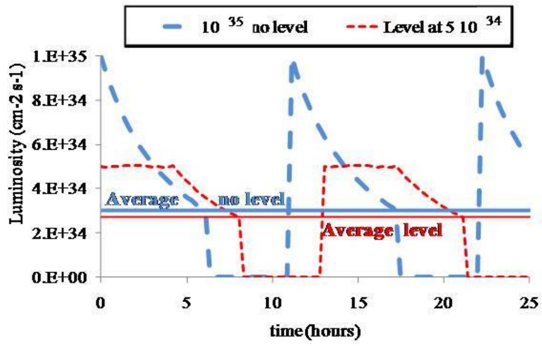

Figure 1: *Typical pattern targeted for the luminosity production in the HL-LHC (courtesy of E. Todesco)*

minosity of 250-300 fb^{-1}/year. Finally, assuming as usual two third of the year (240 days) dedicated to operation and a bit more than one good physics fill achieved in average per day, the HL-LHC target can be transposed into an integrated luminosity of about **1 fb^{-1} per fill**.

In agreement with the experiments, the general consensus is to run with an instantaneous luminosity not exceeding $5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [7], which will have to be sustained during a couple of hours using some leveling techniques not yet decided and never tested so far in any other machine (using crab-cavities, if available, the crossing-angle or β^*, see e.g. [4]). After this first period, a second period of typically 3 hours will follow where the peak luminosity will decay up to a point where, depending on the average turn around time, it will be advisable to dump the beam and refill the machine in order to maximize the daily integrated luminosity.

As illustrated in Fig. 1 assuming some upgrade scenario, the typical coast duration is not expected to exceed one third of the daily operation time of the HL-LHC, i.e. not more than one shift. This confirms a posteriori the above (possibly conservative) assumption of about one good physics fill delivered in average per day, keeping a realistic margin reserved for the machine turn around time, possible delays due to machine unavailability and short technical stops. The other very important information contained in Fig. 1 is that the potential peak luminosity which is available or, let say, "stored" in the machine shall be typically a factor of 2 higher than the target specified for the leveled luminosity. In this respect, the effective target of the HL-LHC is not really relaxed with respect to the one initially defined in the framework the sLHC project, at least in the sens of a "virtual" peak luminosity of $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, but which is not usable in practice due to various limitations, either coming from the machine (e.g. beam-beam) or from the detectors (e.g. so-called "pile-up"). As a result, from the injector and HL-LHC designer point of view, the HL-LHC target will then require to push both the beam parameters and the LHC optics, and in particular β^* well beyond the limits identified for Phase I.

In order to already give some orders of magnitude but also to introduce the potential of flat collision optics (i.e. with $\beta_x^* \neq \beta_y^*$), Fig. 2 shows the peak luminosity as a function of β^*_{X} in the crossing plane for different value of β^*, namely $\beta^*_{||}$, in the other plane, choosing a typical normalised crossing angle of $10\,\sigma$ and assuming the nominal 25 ns bunch spacing (2808 bunches) at ultimate intensity ($1.7\,E11$ proton/bunch), nominal emittances ($\gamma\epsilon = 3.75\,\mu$m in both transverse planes) and bunch length ($\sigma_z = 7.5\,$cm). On the same figure, the case of a round optics (i.e. with the same β^* in both planes) is superimposed. Contrary to the case of a round collision optics where, due to the well-known geometric loss factor, the luminosity saturates rather quickly below a β^* of the order of 30 cm, flat optics possess two interesting features. First of all, for any value $\beta^*_{||}$ chosen in the plane perpendicular to the crossing plane, the luminosity shows an optimum for a specific value chosen for β^*_X in the crossing plane. This β^* can be called the Piwinski β^* since, neglecting the hour glass effect, it corresponds to a Piwinski angle of exactly 1 rad (see [3] for an analytical proof):

$$\frac{\partial \mathcal{L}}{\partial \beta^*_{\mathrm{X}}} = 0 \text{ for } \beta^*_{\mathrm{X}} \sim \beta^*_w \equiv \alpha\sigma_z \,, \tag{1}$$

with α denoting the half normalised crossing angle, that is typically 5 for the LHC, which corresponds to an optimum β^*_X of about 30-35 cm. Then sticking to the Piwinski β^* in the crossing plane, and reducing $\beta^*_{||}$ in the other plane, the luminosity still increases with $1/\sqrt{\beta^*_{||}}$, till saturating due to the hour glass effect. Consequently a natural choice for a flat collision optics is a target β^* of the order of

$$\beta^*_{||} \sim \sigma_z = 7.5\,\mathrm{cm} \tag{2}$$

in the plane perpendicular to the crossing plane. This then

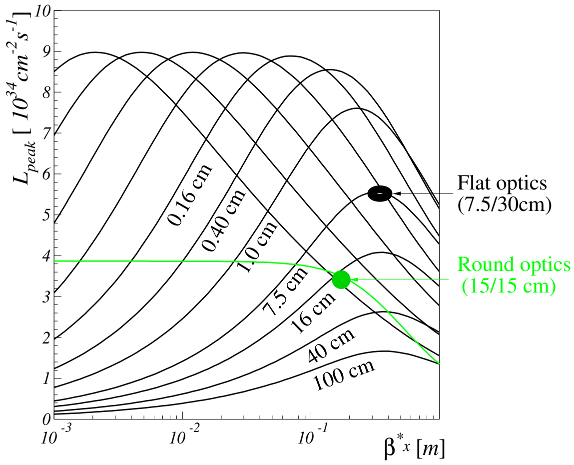

Figure 2: *Peak Luminosity as a function of β^* in the crossing plane for different values of β^* in the other plane (full crossing angle of $10\,\sigma$, so-called "ultimate" beam parameters with 25 ns bunch spacing, 1.7E11 p/bunch, $\gamma\epsilon = 3.75\,\mu m$, $\sigma_z = 7.5\,cm$). The green line stands for the case of round collision optics ($\beta^*_x = \beta^*_y$).*

corresponds to a Piwinski β^* of the order of

$$\beta_X^* \sim \beta_w^* = 30\,\mathrm{cm} \tag{3}$$

in the crossing plane, assuming a typical full crossing angle of 10σ. Under these conditions, the peak luminosity calculated with the so-called "ultimate" LHC beam parameters reminded above, is equal to $5.6 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This is still a factor of about 2 less than a "virtual" luminosity target of 1E35, but substantially higher than the peak luminosity of $3.5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ which would be obtained with an equivalent round optics, i.e. with $\beta_X^* \equiv \beta_{||}^* = \sqrt{7.5 \times 30} =$ 15 cm (see Fig. 2).

Assuming the presence of crab-cavities with ideal performance, the round and the flat optics would give a similar virtual luminosity of the order $8 - 9 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with of course a clear preference for the round optics in this case. In the contrary case, the beam parameters would have to be pushed beyond or well beyond their design values, in terms of bunch charge and/or emittance, in order to find the factor of 2 (for the flat optics) to 3 (for the round optics) still missing in order to meet the effective target of the HL-LHC. In any case, with or without crab-cavity, a novel optics scheme is then hardly needed for the HL-LHC, in order to push β^* below or far below the hard limit of $\beta^* = 30$ cm which was identified in the context of Phase I Upgrade, that is to open a new β^* territory that new Nb3Sn triplets, alone, can certainly not reach.

THE ACHROMATIC TELESCOPIC SQUEEZING (ATS) SCHEME

Phase I optics limitations.

As soon as the triplet is equipped with new low-β quadrupoles of sufficiently large aperture (e.g. 120 mm for Phase I instead of 70 mm for the existing MQX type magnets), severe optics limitations coming from the "non-IT side" of the machine have been identified in the context of the Phase I Upgrade project [2]. While of different nature, all these limitations can be quantified and ranked with the maximum possible peak β-function which is reached in the inner triplet, namely β^{max}, and then can be matched to the regular optics of the arcs, within the aperture and the gradient limits of the IR magnets, but also "chromatically correctable" (in terms of Q' but also off-momentum β-beating) within the strength budget of the sextupole scheme. This β^{max} limit is therefore not influenced by the technology of the inner triplet triplet (Nb-Ti or Nb3Sn) but only depends on constraints coming from the "non-IT side" of the machine. This limit then corresponds to an optimum aperture for the new triplet (with some basic assumptions concerning the beam emittance, the crossing angle and the tolerance budget). Finally, depending on the technology, the IT aperture obtained hereabove fixes the length and the operational gradient of the low-β quadrupoles, which ultimately gives a minimum possible β^* (see Tab. 1 in the case of the Phase I upgrade).

Limitation	β_{Ring}^{max} [km]	β_{min}^* [cm] (for Nb-Ti)
Matching section aperture	~ 13	26
Optics flexibility	~ 17	21
Chromatic aberration	~ 11	30

Table 1: *Phase I optics limitations expressed in terms in maximum possible peak β-function reached in the inner triplet and corresponding minimum possible β^* for an Nb-Ti triplet [2]. The Nb3Sn technology can push all these limits by 25%. The aperture related limit stands for the existing D2, Q4 and Q5 of the matching section. The so-called optics flexibility limit is reached when at least one quadrupole magnet (in practice several) runs below 3% or above 100% of its nominal gradient. The chromatic limit stands for the nominal current of 550A in the lattice sextupoles, and assumes that two sectors of sextupoles are used for the chromatic correction of one single triplet.*

Within a good approximation, this minimum β^* is constrained by the following scaling law [2]:

$$\beta_{min}^* \propto \frac{1}{\left(\beta_{Ring}^{max}\right)^{3/4} \sqrt{B_{\mathrm{peak}}}}\,, \tag{4}$$

where, on one hand, the β_{Ring}^{max} limit depends only on the optics limitations imposed by the "non-IT side" of the machine and, on the other hand, the critical field B_{peak} is given by the triplet technology. Passing from the Nb-Ti to the Nb3Sn technology for the new triplet should give a jump by 50% for B_{peak}, therefore corresponding to a reduction of β_{min}^* by 25%. This gain looks quite modest compared to the factor of 2 to 4 which are needed to operate the HL-LHC with a β^* of 15 cm or even twice below for a flat collision optics (see previous section). A much more promising approach therefore consists in elaborating a global optics scheme which would be able to relax the constraints imposed by the "non-IT side" of the machine, that is to increase by a big factor the β_{Ring}^{max} limit occurring in the previous scaling law.

The ATS scheme

The idea of this novel scheme was imagined a few years ago by the author when realizing the severe optics limitations of the Phase I project. Only its name and corresponding acronym was very recently invented. This new concept and its implications in terms of hardware changes in the LHC ring have been already documented in 2010 [3] together with its effective implementation in terms of optics and layout and first analysis [8, 9]. Hereafter, the basic principle and a few illustrations are given for the optics and its fundamental chromatic properties.

Motivations and basic idea. As shown in Tab. 1, the Phase I optics limitations were given by

- the mechanical acceptance of the matching section,
- the gradient limits of the IR quadrupoles,
- the strength limits of the arc sextupoles.

Concerning the first limitation, the only solution is to rebuild new two-in-one magnets of larger aperture, in particular to replace the existing D2, Q4 and Q5 (see later), with of course some limits still to be clearly specified in this case (i.e. taking into account the nominal separation of 194 mm between the two beams at D2 and beyond). Concerning the very poor optics flexibility of the experimental insertions IR1 and IR5 observed at low β^*, where some quadrupoles of the matching section (Q5 and/or Q6) shall operate a very low gradient and other magnets belonging to the dispersion suppressor (Q7 and QT12/13) tend to run out of strength, one possibility is to allow floating matching conditions at the boundaries of these insertions in order to relax the internal constraints. More precisely the idea is to maintain the dispersion matching constraints at the entry and exit of the low-β insertions (from Q13.L to Q13.R) but to allow the "auxiliary" insertions on either side (IR8/2 for IR1 and IR4/6 for IR5) to contribute to the matching of the β-functions, at least below a certain β^*. As a result, β-beating waves will be induced in the sectors adjacent to the low-β insertions (s45/56 for IR5 and s81/12 for IR1). Assuming a phase advance per arc cell strictly matched to $\pi/2$ in these sectors, and if correctly phased with respect to the IP, these waves will reach their maximum at every other sextupoles, i.e. at the sextupoles which belong to the same electrical circuit in the LHC. Consequently, the chromatic correction efficiency of these sextupoles will drastically increase at constant strength which, de facto, will be a definite cure for the third limitation previously mentioned.

The reasons why this new scheme is particularly well-suited to the LHC are two-folds.

- Due to the large dynamic energy range of the machine from 450 GeV to 7TeV and the reduction in proportion of the transverse physical emittances of the beam, the peak β-functions in the arcs can be increased by a factor of about 16 at flat top energy without exceeding any aperture related limits.
- At flat top energy, the quadrupole magnets of the so-called "auxiliary" insertions are either moderately pushed, which is the case for the experimental insertions IR8 and IR2 assuming a β^* of a few meters in pp collision mode, or not pushed at all, in the case of IR4 and IR6 for which the injection optics is kept constant at flat top energy.

Therefore all the ingredients are already available in the existing machine in order to blow up the β-functions in the arcs 81/12/45/56 at 7 TeV and then implement the ATS scheme.

Implementation and illustration. A comprehensive description of this new scheme can be found in [3], in particular concerning the phase constraints imposed on the left and right side of the low-β insertions and the squeeze performed in a two stage telescopic mode. More detailed analysis and illustrations, in particular showing the variation of the optics of the "auxiliary insertions" IR8, IR2, IR4 and IR6 during the squeeze, are presented in [8]. The flat collision optics discussed in the previous section is then illustrated in Fig. 3 with $\beta^*_X = 30$ cm in the crossing plane and 7.5 cm in the other plane. In this particular case, it is assumed that the plane of smallest β^*, and therefore the crossing plane which is perpendicular, is alternated between IR1 and IR5 in order still to ensure a partial compensation of the long range beam-beam interactions between the two high luminosity insertions (see later). However any other possible combination have been successfully rematched and the corresponding collision optics implemented in the so-called SLHCV3.0 repository [9]. The round collision optics with $\beta^* = 15$ cm at IP1 and IP5 developed more recently for the fourth crab-cavity workshop [10] is also available at the same address. Within the exception of the Q5 quadrupoles of IR6 which needs to be made 20 to 25% longer (and more deeper modifications obviously needed in LSS1 and LSS5, see later), all these optics have been found fully compatible with the existing hardware and layout of the "auxiliary" insertions IR8, IR2, IR4 and IR6.

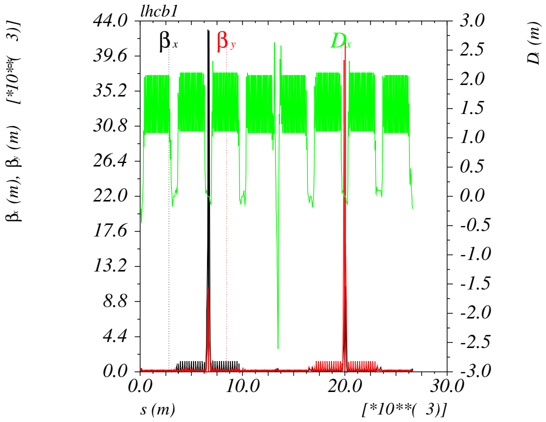

Figure 3: *Alternated flat collision optics for the HL-LHC with $\beta^*_{x,y}=7.5/30$ cm at IP1 and $\beta^*_{x,y}=30/7.5$ cm at IP5. Starting from a pre-squeezed optics with $\beta^*_{x,y} = 60$ cm, β-beating waves are induced in the sectors 81, 12, 45 and 56 with peak values increased by a factor of 2 or 8 with respect to the regular FODO optics.*

From the optics point of view, the high luminosity insertions therefore cover a much larger fraction of the machine, containing three optical modules with well-distinguished functionalities:

- the low-β insertions proper which become strictly passive below a so-called "pre-squeezed β^*". The latter is defined as being the minimum possible β^* for which the chromatic correction of each triplet can be performed by only one sector of lattice sextupoles (contrary to the Phase I scheme which counted on 2 sectors per triplet). Assuming the existing sextupole scheme of the LHC arcs and a reference gradient of 100 T/m for the new triplet (compatible with an aperture of 150 mm for the Nb-Ti technology), the pre-squeezed β^* is of the order of 60 cm.

- the "auxiliary" insertions IR8/IR2 and IR4/IR6 which plays the role of matching section in order to squeeze IR1 and IR5 further down.
- two interleaved horizontal and vertical chromatic correction sections which are supported by the lattice sextupoles of the sectors located on either side of IR1 and IR5 (s45/s56 for IR5 and s81/s12 for IR1). Due to the β-beating waves induced in the arcs, the correction efficiency of the sextupole increases with $1/\beta^*$ at constant strength, and the chromatic limit is therefore never reached in this way.

With this construction, the peak β-functions β^{max} reached in the IT can then largely exceed the Phase I limits given in Tab. 1, but paying the price of an increase of the peak β-functions in the arcs by a factor of 2 to 8 starting from a pre-squeezed optics with $\beta^* = 60$ cm.

Chromatic properties. The chromatic properties of the ATS scheme are illustrated in Fig. 4 in the case of the flat optics. The chromatic variations of the betatron tunes are almost linear over a rather large momentum window of ± 1.5 permil (which basically corresponds to the opening of the momentum collimators at flat top energy). The chromatic Montague functions (giving the amplitude of the first order chromatic derivative of the β-functions) are nicely vanishing in the collimation insertions IR3 and IR7 and at IP1 and IP5. Another important feature which is not visible in the previous picture is that, in each of the two planes, the off-momentum β-beating waves induced by the lattice sextupoles are exactly in quadrature of phase with the β-functions themselves, in particular in the triplet and its neighboring magnets. Therefore, no further degradation of the off-momentum mechanical aperture is induced in the arcs, the matching section and the new triplet, except the usual one coming from the contribution of the dispersion, which remains nominal and perfectly matched in the ATS scheme. Finally an extremely important quantity to control is the spurious dispersion induced by the crossing scheme in IR1 and IR5. The latter can reach up to 10 m in the new IT, produced by one of the two high luminosity insertions and then exported in the other one. However, thanks to the specific phasing conditions imposed in the ATS scheme, very modest H or V orbit bumps of the order of 2.5-3 mm generated in the sectors adjacent to IR1 and IR5 are found to be sufficient to bring it back to a level of a few tens of centimeters (see [3] for more details).

Sextupole scheme. Before closing this section, a specific discussion is needed concerning the existing sextupole layout. In order to reach a "decent" β^* of 30 cm for Phase I, two sectors of sextupoles with specific constraints

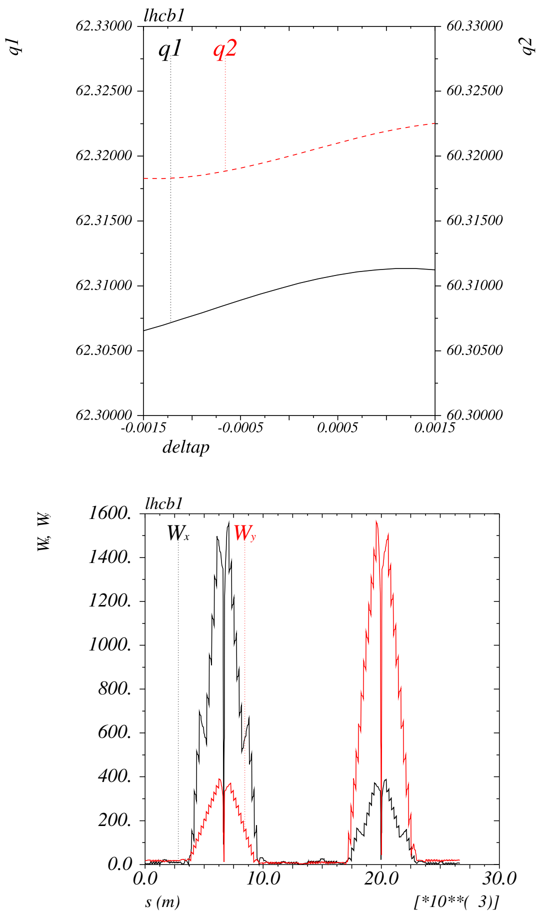

Figure 4: *Chromatic variation of the betatron tunes (top) and chromatic Montague functions along the machine starting from IP7 (bottom) for the alternated flat collision optics showed in Fig. 3.*

of phase advance between them and with respect to the IP, were needed for the chromatic correction of one single triplet. Below this β^*, half of the defocusing sextupole circuits were pushed above 550A. This scheme made the optics very rigid, not only by pushing the LHC IR's at the limit of their tunability range but also generating more or less strong interferences between the correction of the off-momentum β-beating proper and any tune or chromaticity trims performed in operation in the real machine. For the ATS scheme, only one sector sextupoles per triplet is foreseen for the chromatic correction of the squeezed optics. In particular, this explains why, without any additional ingredient (see later), the pre-squeezed optics is presently limited to a β^* of 60 cm (and not 30 cm). Then, in order to squeeze further down, the β-beating waves need to be engaged in the arcs. The net benefit is then to leave free of constraints the four sectors adjacent to the collimation insertions, namely s23, s34, s67 and s78, which makes the overall optics much more flexible and tunable in operation. In particular, even when the optics is squeezed in IR1 and IR5, the sextupoles belonging to the sectors 23, 34, 67 and

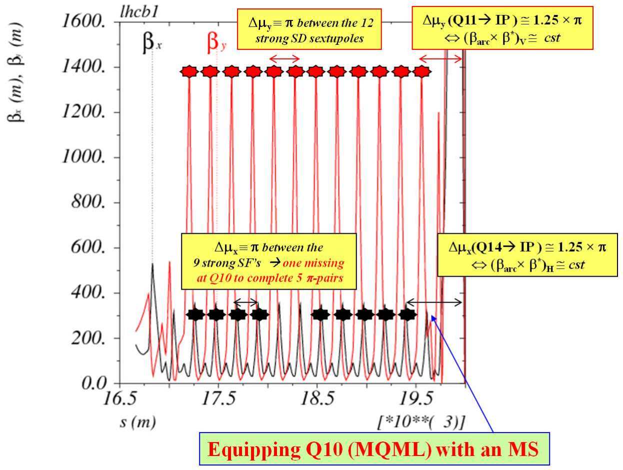

Figure 5: *Flat collision optics (beam 1) zoomed in between IP4 and IP5. The focusing and defocusing sextupoles correcting the triplet are indicated by the black and red spots (2 SF's close to mid-arc are replaced by skew sextupoles), with phase advance constraints imposed between them and with respect to the IP. Equipping Q10 with an additional sextupole warrant an almost perfect self-cancellation of the geometric aberrations induced.*

78 still keep their 7 TeV equivalent injection setting. This represents a huge reserve for any chromaticity trim in operation or, turned differently, for a third low-β experiments, such as for instance an e-p experiment (LHeC), but located in IR3 or IR7. On the other hand half of the sextupoles are pushed to very high field in the four sectors adjacent to IR1 and IR5 (550A for half of the defocusing sextupoles SD's and around 300 A for the SF's which are about twice more efficient due to the larger dispersion at the QF's). By construction, the β-beating waves are also maximum at the locations of these strong sextupoles. In order to avoid a sharp excitation of the third order resonances and keep under control the tune spread induced by these strong sextupoles, a natural requirement is that the sextupoles participating to the chromatic correction can be paired by π, which means in particular an even number of SF's and SD's dedicated to each triplet. However, as illustrated in Fig. 5, for a given beam and a given side of the high luminosity insertion, there is always one plane where it is not presently the case: one SF/SD is missing for beam1 on the left/right sides of IR1 and IR5, and conversely for beam2 due to the optics antisymmetry. Therefore two possibilities are offered, either removing one sextupole from each circuit under concern (e.g. at Q14) or add a new one with a preference for Q10 on the left and right sides of IR1 and IR5 (basically exchanging the long MCBC orbit corrector equipping the MQM type cold masses with a standard dipole sextupole corrector MSCB equipping the SSS's). Assuming no strength limitation in the sextupoles, the two options gives very similar improvements in terms of dynamic aperture and tune

Optics	Pre-squeezed	"2222"	"4444"	"8228"
$\beta^*_{x,y}$ [cm]	60	30	15	$7.5 \leftrightarrow 30$
Peak $\beta^{arc}_{x/y}$ [m]	180 (nom.)	350 (H and V)	700 (H and V)	1400 $\leftrightarrow 350$
Min. DA [σ]	> 50	28	15	11

Table 2: *Minimum* 10^5 *dynamic aperture v.s. optics without including yet any field imperfection in the new IT and the new elements (D1/D2/Q4/Q5) of LSS1 and LSS5 [8].*

spread [8]. The first one would even be cleaner, since the β functions at Q10 differ already slightly from the ones of the regular arcs and the phase advance from Q14 to Q10 is no longer exactly π. However in the present situation where the pre-squeezed optics is already limited by the available strength of the sextupoles, the difference between the two options correspond to a difference of about 20% in terms of peak β-functions in the arcs at constant β^* in physics or, said differently, to a possible downgrade of β^* by 20% taking into account certain limits imposed on the arc optics (see next section). This 20% difference is then very similar to the possible improvement by 25% that the Nb3Sn technology could bring to the overall system. Equipping the Q10's with lattice sextupoles in IR1 and IR5 is then more than justified in this sens.

WEAK POINTS, MITIGATION MEASURES AND OTHER IMPLICATIONS

Increasing the β-functions in the arcs has obviously several implications and draw-backs. The main worry concerns the impact on the dynamic aperture (DA). This item will be addressed in the next paragraph together with a series of possible mitigation measures. Other implications will then be mentioned, some of them being particularly surprising. Finally a critical overview of the situation, not specific to the ATS scheme but concerning the triplet requirements at low β^*, will be given in the last paragraph of this section.

Optimizing the telescope to preserve the DA

A net degradation of the dynamic aperture is expected due to the increase of the β-functions in the LHC arcs, combined with the strong sextupoles involved in the chromatic correction and the field quality of the arc magnets (dipoles and quadrupoles). Without including yet any field imperfections in the new triplets and D1's, but assuming that the quadrupoles Q10 will be equipped with a lattice sextupole in IR1 and IR5 (see previous discussion), the dynamic aperture of the machine has been calculated for various collision optics, starting from the pre-squeezed optics [8]. For each optics considered, the results obtained have been quantified by one single number representing the minimum 100'000 turns dynamic aperture calculated over 5 angles of the phase space and 60 different possible configurations of the as-built machine. As shown in Tab. 2 for round optics, the dynamic aperture decreases more or less linearly with the increase of the β-functions in the LHC arcs. In the case of the flat optics, the DA is only 11σ.

At this stage, it is rather difficult to give a precise specification for this quantity, in particular because the field quality of the new triplet is not known. On the other hands, several elements are already available to justify an improvement of the situation by about 40%, i.e. a global reduction of the β-functions in the arcs by the same amount, in particular below the 1 km level for the flat optics. Indeed a dynamic aperture of 11 σ which is mainly driven by the field quality of the main dipoles and quadrupoles of the lattice corresponds exactly to the situation of the LHC at injection where it is a priori excluded to collide bunch trains (i.e. with both head-on and long-range beam-beam interactions). Then, deriving a first estimate for the field quality targets of the new triplet, and betting on a coil aperture of 150 mm, we will see later that the contribution of the triplet alone should also correspond to a dynamic aperture in the range of 11 σ and 15 σ for the 7.5/30 cm flat and the 15 cm round optics, respectively. In this respect, the dynamic aperture calculated by considering only the contribution of the arcs should be in the shadow, with a corresponding dynamic aperture of at least 20 σ and 15σ for the round and flat optics, respectively, i.e. about 40% larger than the values obtained in Tab. 2.

The mitigation measures are simple. First of all, the pre-squeezed optics with $\beta^* = 60$ cm needs to be further pushed in order to reduce in the same proportion the amplitude of the β-beating waves in the arcs at a given β^* in physics. The pre-squeezed optics is presently limited by the sextupole strength available in the defocusing sextupoles SD's, with still a big margin available in the SF's. Therefore 10% can be gained operating the sextupoles at the ultimate current of 600A, which has been already validated for all of them during the cold tests of SM18, and with training quenches observed only in a few cases (see e.g. the minutes of the Magnet Evaluation Board). Another gain resulting from the installation of a lattice sextupole at Q10 (see previous section) will allow to push further down the pre-squeezed β^* by about 10%. Finally, combining the two above measures and the substantial margin still existing in the focusing sextupoles, a flat pre-squeezed optics with $\beta^*_{x/y} = 30/50$ cm would be perfectly reachable, in a configuration where both the SF's and the SD's would operate at 600A and assuming a (100 T/m-150 mm) inner triplet. Should not it be sufficient to restore a decent dynamic aperture, at least for the most critical optics (i.e. the flat optics), the Nb3Sn technology, if available to build a (150 T/m-150 mm) triplet, will offer an additional reduction of the pre-squeezed β^* by 25% at constant sextupole strength, i.e. the same reduction of the β-functions in the arcs and the same relative improvement in terms of dynamic aperture at constant β^* in physics. Finally, relaxing β^* in physics from 7.5 cm to 10 cm in the plane perpendicular to the crossing plane corresponds to a Piwinski β^* of 36 cm (instead of 30 cm) in the crossing plane. With a new triplet based on the Nb-Ti technology, this ultimate measure would then restore a rather safe situation, almost identical to the one discussed above assuming Nb3Sn low-β quadrupoles and at a very modest cost in terms of luminosity: a performance loss by only 10% for an increase of $\beta^*_{x,y}$ by 20-30%, due to the small sensitivity of the luminosity v.s. β^* in the crossing plane when operating in the vicinity of the Piwinski β^*, and the saturation due to the hour-glass effect which disappears very quickly at $\beta^* = 10$ cm in the other plane.

To summarise, at a maximum cost of 10% in terms of performance and counting on a modest upgrade of the sextupole scheme in the sectors 81, 12, 45 and 56, the dynamic aperture of the collision optics (flat or round) should no longer be influenced by the implementation of the ATS scheme, but only by the field quality of the new triplet and, of course, by the beam-beam effect.

Other implications specific to the ATS scheme

The ATS scheme has a series of other implications which are listed below, some of them being very surprising and all of them being relevant enough to require a detailed analysis. Most of these implications are however related to the increase of the β-functions in the arcs and therefore will be mitigated by the different measures previously discussed.

Operational aspects. A modification of the IR4 and IR6 optics during the squeeze is a clear specificity of the ATS scheme. Optics solutions can in general be found preserving as much as possible (i.e. within 20-30%) the twiss parameters in the core of these two insertions where most of the instruments and equipments are hosted. One exception however has to be kept in mind. It concerns the dispersion suppressor on the right side of IR4, which contains several BPMs presently used by the damper system, while the β-beating waves are already important in this part of the ring.

Another operational aspect which is worth to be mentioned is an increased sensitivity of the beam to the linear field imperfections located in the arcs adjacent to the high-luminosity insertions. If the correction of these imperfections is not local enough, that is at least sector by sector for a_2 and b_2, their impact on the beam will be magnified, e.g. in terms of closed orbit, coupling or β-beating, in proportion to the increase of the β-functions in the arcs during the second part of the squeeze. On the other hand, if local or sector by sector corrections are properly achieved, simulations have shown that this side-effect is a non-issue. Then, in the real machine, thank to the global orbit feed-back of the LHC and/or any feed-forward techniques which would be applied during the commissioning of the new squeeze, this aspect should represent an addtionnal complication but a priori not a real show-stopper for the ATS scheme.

Optics	T_x [h]	T_z [h]
"1111"	$78 \rightarrow 49$	$47 \rightarrow 29$
"2222"	$69 \rightarrow 44$	$49 \rightarrow 31$
"8228"	$59 \rightarrow 36$	$56 \rightarrow 35$

Table 3: *Horizontal and longitudinal emittance growth time due to IBS at 7 TeV with $N_b = 1.7E11$ p/bunch and $\gamma\epsilon = 3.75$ µm (courtesy of A. Vivoli) for different optics (see Tab. 2 for the corresponding peak β-functions in the arcs), and two different possible bunch lengths: 7.5 cm (2.5 eV.s) $\rightarrow$ 6.0 cm (1.6 eV.s).*

Collimation and machine protection. With peak β-functions increased by up to a factor of 8 in the LHC arcs, the normalised aperture of the main magnets shrinks down to $n_1 \sim 10 - 11$ at 7 TeV in the sectors adjacent to the high luminosity insertions. Possible implications in terms of collimation inefficiency or machine protection need then to be addressed.

Effective impedance, Landau damping and "footprint shaping". The increase of the β-functions averaged over the eight arcs of the ring is around 60-70% in the worst case (flat optics). The effective beam-screen impedance seen by the beam will then increase in the same proportion at 7 TeV, and therefore the imaginary part of the coherent tune shift and the instability rise times. However, since only the beam-screen impedance is concerned, we should not forget that the situation at injection will always be much worst (by a factor of about 10 in terms of rise time [11]) and is already proved to be under control via the transverse damper, at least for eventual multi-bunch instabilities. Concerning possible single bunch instabilities, it is then worth noting that, as for the sextupoles, the efficiency of the Landau octupoles is widely improved by the ATS scheme, e.g. by more than one order of magnitude in both planes for the alternated flat optics. More generally speaking, this feature of the ATS scheme leads to an exceptional situation for a circular collider where non-linear corrector magnets would become efficient enough for shaping the tune spread induced by the beam-beam collisions (but at a possible cost not yet evaluated in terms of dynamic aperture and other side effects as the second order chromaticity Q'' induced by the MO circuits of the LHC arcs).

Intra-beam scattering. Last but not least, a significant sensitivity of the IBS growth rate has been observed with respect to the choice of the collision optics. This variability is again driven by the sharp modifications of the β-functions in half of the machine when the optics is squeezed. Starting form the pre-squeezed optics (with the nominal β's in the arcs), the tendency is a net degradation of the IBS growth time by 30% in the horizontal plane but a significant improvement in the longitudinal plane, which is generally the most critical plane with respect to IBS for the LHC (see Tab. 3). In the extreme case of the flat optics "8228", the horizontal and longitudinal IBS growth times are very similar, of the order of 35 hours for the ultimate charge per bunch, the nominal transverse emittances and assuming a longitudinal emittance already reduced to 1.6 eV.s (corresponding to an r.m.s. bunch length of 6 cm for the nominal 16 MV RF voltage of the LHC).

Implications for the IT when running at low β^*

Regardless of the specificities of the ATS scheme, it is worth reminding the severe requirements imposed on the new triplets when running at a very low β^*, or more precisely at a β^{max} in the range of 20 km or 40 km for the round and flat optics presently discussed.

IT stability. The tolerance of the new triplet to mechanical vibrations and PC jitter shall be improved with $1/\sqrt{\beta^*}$ and $1/\beta^*$, respectively, with respect to the existing triplet. More precisely, by requesting a control of the transverse position of the IP within one tenth of a sigma and by imposing tune ripples due to PC jitters not exceeding the 10^{-4} level per triplet, the sub-micron level is reached for the alignment control of the low-β quadrupoles, together with the sub-ppm level for the short-term stability of the power supplies feeding the triplet:

$$\begin{array}{lll} \delta x^* \lesssim \sigma_x^*/10 & \Rightarrow & \delta x_{IT} \sim 0.75 \rightarrow 0.5\ \mu\text{m} \\ \Delta Q \lesssim 10^{-4} & \Rightarrow & \Delta I/I_{max} \sim 1 \rightarrow 0.5\ \text{ppm}\,, \end{array} \tag{5}$$

for $\beta^* = 15 \rightarrow 7.5$ cm and assuming a reduced normalised emittance of 2.75 µm (see later).

IT field quality. A preliminary target error table can be easily 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:

$$\frac{[b_n(R_{r_{\rm new}})]_{\rm Target}}{[b_n(R_{r_{\rm old}})]_{\rm MQXB}} \equiv \left(\frac{(\beta_{IT}^{max})_{\rm old}}{(\beta_{IT}^{max})_{\rm new}}\right)^{n/2} \times \left(\frac{R_{r_{\rm new}}}{R_{r_{\rm old}}}\right)^{n-2}\,, \tag{6}$$

with $R_{r_{\rm old}} \equiv 23.3$ mm denoting the reference radius used to define the multipole components of the existing MQXB type magnets (at 2/3 of the 70 mm aperture), which would correspond to $R_{r_{\rm new}} = 50$ mm for a new triplet with a coil aperture of 150 mm.

Round optics with $\beta^* = 15$ cm. Taking $(\beta_{IT}^{max})_{\rm old} \approx 4.5$ km for the peak β-function reached in the existing triplet at the nominal collision β^* of 55 cm, and $(\beta_{IT}^{max})_{\rm new} \approx 21$ km for the round optics with $\beta^* = 15$ cm, we simply get

$$\frac{[b_n(R_{r_{\rm new}})]_{\rm Target}}{[b_n(R_{r_{\rm new}})]_{\rm MQXB}} \sim \left(\frac{R_{r_{\rm old}}}{R_{r_{\rm old}}}\right)^2\,. \tag{7}$$

Roughly speaking, the above relation corresponds to a fraction of a units for the low-order multipoles at two third of the aperture of the new triplet. This may well rule out the

Nb3Sn technology for the HL-LHC triplet if no big improvement is made in this direction in the coming years. Furthermore, these targets are already a factor of about 2 (more precisely a factor 150/70) more demanding than the "natural" gain expected in terms of field quality with NbTi quadrupoles of larger aperture [12]. On the other hand, the dynamic aperture of the LHC in collision is about $15\,\sigma$ for two insertions squeezed to $\beta^* = 55$ cm [13]. In addition, the triplet correction (concerning all multipoles below $n = 6$, except a_5, b_5 and a_6) looks rather inefficient to improve further the situation [13]. This means that the 15σ dynamic aperture level may be actually driven by the a_5, b_5 or a_6 field imperfections of the existing triplet, in which case equipping the new IT with such corrector coils will relax the target on these multipoles at least by the factor of 2 requested above. Then a second possibility would be that this $15\,\sigma$ DA level is in fact driven by multipoles of order larger of equal to $n = 7$. In this case, relaxing the above targets by a factor of 2 should not degrade the dynamic aperture by more than 10% (more precisely with a factor $2^{1/(n-2)}$ with $n \geq 7$). Assuming that the scaling law derived in [12] will be verified for a new NbTi triplet of 150 mm aperture, and counting eventually on new corrector coils to equip the new triplet (a_5, b_5 or a_6 in addition to the existing types), the round optics with $\beta^* = 15$ cm should then correspond to a dynamic aperture in the range of $14 - 15\sigma$.

Flat optics with $\beta^*_{x/y} = 7.5/30$ cm. A further degradation of the dynamic aperture by a factor $\sqrt{2}$ is expected when increasing β_{max} by a factor of 2 in one of the two transverse planes and reducing it by the same amount in the other plane. This expectation might be a bit pessimistic for a flat collision optics where the plane of smallest β^* is alternated between IR1 and IR5, and the peak orbit excursion due to the crossing angle occurs in the plane of smallest β^{max} (see e.g. [14] where several DA calculations were performed to compare the nominal LHC collision optics with possible flat optics with a β^* aspect ratio of 4). Under these conditions, the 7.5/30 cm flat optics should lead to a dynamic aperture in the range of $10\,\sigma$, probably $11\,\sigma$ but hardly more. This value is substantially less than the dynamic aperture calculated with the nominal collision optics of the LHC but remains compatible with the design value of $10\,\sigma$ which was targeted in collision in the early design of the machine [15].

As already mentioned, this last consideration fully justifies the need of further optimizing the pre-squeezed optics in order to reduce the peak β-functions reached in the arcs and therefore keep their impact on the dynamic aperture well in the shadow of that of the new triplet. Finally, this demonstrates as well that a β^* of 7.5 cm is probably at the limit of feasibility for the HL-LHC (at least at nominal transverse emittances), even if substantial margins still exist in the matching quadrupoles of IR8, IR2, IR4 and IR6 in order to squeeze even further the high luminosity insertions using the ATS techniques.

HARDWARE CHANGE REQUESTS

The implementation of the ATS scheme only requires few hardware modifications in the LHC ring, without counting of course the ones needed in the long-straight sections LSS1 and LSS5 (magnets with larger apertures). These modifications have been already defined in [3] and are reminded below.

Sextupole scheme

As already discussed, the sextupole scheme shall be upgraded in the sectors 81, 12, 45 and 56 with

- a re-commissioning of the circuits at the ultimate current of 600A.
- the implementation of an MSCB (dipole sextupole) corrector in the four Q10 quadrupoles (MQML type) located in the dispersion suppressors of IR1 and IR5.

The second measure is mandatory for minimizing the large geometric aberrations induced by the sextupole circuits participating to the chromatic correction of the triplet. Then, the two above measures, if combined together, enable a reduction by 20% of the peak β-functions reached in the arcs for a given β^* targeted in physics, and therefore the same relative improvement in terms of dynamic aperture.

"Auxiliary insertions IR8, IR2, IR4 and IR6"

Within only one exception, the existing layout of IR8, IR2, IR4 and IR6 is fully compatible with the new optics functionality requested by the ATS scheme, i.e. the generation and absorption of β-beating waves in the sectors 81, 12, 45 and 56. The only exception concerns the Q5 quadrupoles of IR6 (MQY), which would need 20 to 25% more integrated strength. A natural proposal would be to develop a longer version of the existing MQY type, namely an MQYL type, that is with a magnetic length of 4.8 m equal to that of the MQML type quadrupoles, compared to 3.4 m for the standard MQY and MQM type magnets.

LSS1 and LSS5

Inner triplet, D1 and corrector package. Reducing β^* requires obviously an inner triplet (IT) and a separation dipole (D1) of larger aperture. Considering the nominal emittance $\gamma\epsilon = 3.75\,\mu$m, the flat optics illustrated in Fig. 3 (with $\beta^*_{\mathrm{X}} = 30$ cm and $\beta^*_{||} = 7.5$ cm) and a normalised crossing angle of $\theta_c = 13\,\sigma$ in the plane of largest β^* (i.e. 535 μrad), and assuming the induced spurious dispersion to be fully corrected by the generation of orbit bumps in the arcs as already discussed, the inner dimension of the beam-screen shall be around 125 mm for the IT quadrupoles and around 135 mm for D1 (see Fig. 6). The corresponding coil apertures are then estimated to 150 mm and 160 mm respectively. These estimates do not include any dedicated shielding in Q2, Q3 and D1 but assume an overall budget of 13 mm for the manufacturing and alignment tolerances

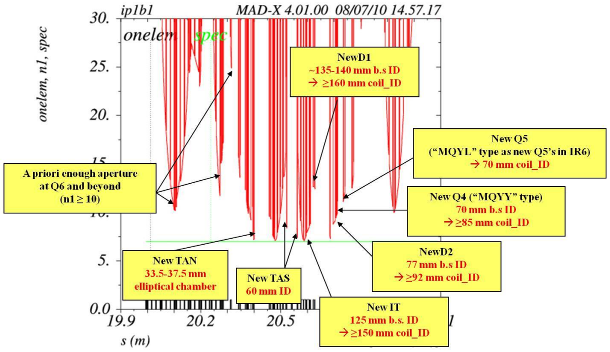

Figure 6: *Required aperture for the new TAS, IT, D1, TAN, D2, Q4 and Q5 in IR1 and IR5 and corresponding aperture plot assuming $\beta^*_{\rm X} = 30$ cm, $\beta^*_{||} = 7.5$ cm, a full crossing angle of $13\,\sigma$ and the nominal emittance ($\gamma\epsilon = 3.75\,\mu$m). The numbers indicated here above have to be understood with an error bar of the order of $\pm 5-6$ %, depending on the technology which will be chosen for the new ~ 150 mm inner triplet, more precisely assuming an operating gradient of 100 T/m (if Nb-Ti) or 150 T/m (if Nb3Sn) for the inner triplet.*

of the cold bore and beam-screen (as directly rescaled from the 11 mm budget which was taken for the Phase I triplet and for which there is very likely some room for improvement). The same figures would be obtained for the round optics with $\beta^* = 15$ cm and a normalised crossing angle of $10\,\sigma$ (i.e. 580 μrad at nominal emittance).

It is important to stress that the above estimates have been obtained with an intermediate gradient of 123 T/m for the inner triplet, more precisely using the IT layout developed for the Phase I IR Upgrade project [2]. For an aperture of 150 mm, this gradient lies almost exactly in between the possibilities offered by the Nb-Ti and Nb3Sn technologies (i.e. about 100 T/m and 150 T/m, respectively). Then, at constant β^* and normalised crossing angle, the beam sizes and orbit excursions reached in the inner triplet and D1 vary approximately with the fourth root of the IT operating gradient. Therefore depending on the technology of the new low-β quadrupoles, the coil apertures specified above have to be understood with an error bar of the order of 5-6%, which corresponds to an aperture range of 140–160 mm for the new triplet.

The main advantage of the Nb3Sn technology is actually elsewhere. Indeed, in all cases, the new inner triplet will have to be longer than the existing one with, consequently, a net increase of the number of parasitic beam-beam encounters in the interaction region (e.g. 21 parasitic encounters on either side of the IP for the Phase I layout [2] compared to 15 for the nominal layout of LSS1 and LSS5). In this respect, a 150 mm aperture Nb3Sn triplet operating at 150 T/m for the LHC Upgrade could eliminate about 3 parasitic encounters with respect to a Nb-Ti triplet of the same aperture.

Then in order to further optimize the layout, the D1 separation dipole shall be installed as close as possible to the inner triplet, in particular by displacing the IT-D1 feed box from the non-IP side of Q3 (as it is presently the case and was the case for the Phase I project) to the non-IP side of D1. Under these conditions the expected gain is of the order of 2 parasitic encounters on either side of the IP.

The type and number of linear and non-linear IT correctors will actually depend on the field quality achieved in the new low-β quadrupoles (and eventually D1). However based on the experience gained during the conception of the nominal LHC and the study of the Phase I project, it is worth noting that a minimal set consists in at least three double plane orbit correctors [16], a skew quadrupole corrector magnet and a b_3 and b_6 correction coil per triplet. Then, as already mentioned, other non-linear coils will certainly be needed to correct a fraction if not all the even and odd multipoles of order lower or equal to $n = 6$. In all cases, nested corrector magnets, in particular combined H and V orbit correctors, will be highly desirable not only to compactify the triplet layout and therefore minimise the peak β-function β^{max} reached in the IT at a given β^*, but also to further reduce the number of parasitic encounters. Under these conditions, indeed, a gain corresponding to slightly more than one parasitic encounter is expected on either side of the IP assuming an optimized IT orbit correction scheme consisting in 3 H/V nested orbit correctors attached to Q2a, Q2b and Q3 [16].

Matching section. With a target β^* as small as the r.m.s. bunch length, new two-in-one magnets with larger aperture are also needed not only for replacing the existing matching section quadrupoles Q4 and Q5 but also the recombination dipole D2. Assuming a clearance of not more than 15 mm between the inner diameter of the coil and that of the beam-screen (including manufacturing and alignment tolerances), the required aperture of these new magnets is reported in Fig. 6. The 70 mm coil aperture of the existing MQY type magnets is perfectly suitable for the new Q5 (presently of MQML type, therefore to be replaced with the new MQYL type discussed for the new Q5's of IR6). On the other hand, Q4 and D2 require a coil aperture of the order of 85 mm and 92 mm assuming the nominal separation of 194 mm and 188 mm, respectively, between the bores of these two magnets. The integrated strength of the new Q4 and Q5 can be kept nominal, while the bending angle of the new D2 will depend on the length of the new triplet or, more precisely, on the distance which will separate the new D1 and D2.

Finally, with a full crossing angle exceeding the 0.5 mrad level, the orbit correctors equipping the new Q4's shall be made stronger than the existing ones [17], if not doubled if the crossing angle is used as the main tool for luminosity leveling (see next section). In this configuration, 50% more strength will also be needed in the orbit correctors equipping Q5 and Q6.

Absorbers The TAS and the TAN need to be rebuilt with a larger aperture (see Fig. 6 for more details). Then, due to the net reduction of the normalised aperture in the matching section ($n_1 \sim 9-10$ compared to $n_1 \sim 14-15$ for the nominal collision optics of the LHC with $\beta^* =$ 55 cm), additional TCT-like absorbers will certainly be needed in order to protect Q4 and Q5 both with respect to the incoming and to the out-going beams.

A COMPLETE SOLUTION FOR THE HL-LHC

The ATS scheme can potentially give a peak luminosity of $5.6E34$ for a flat collision optics pushed to $\beta^*_{x/y} = 7.5/30$ cm and assuming the so-called ultimate parameters of the LHC beams (see Fig. 2). As already mentioned, this performance might eventually be limited at the level of $5E34$, assuming a flat optics relaxed to 10/36 cm in order to mitigate the corresponding increase of the β-functions in the arcs and preserve the dynamic aperture of the machine. Roughly speaking, a factor of approximately 2 is then still missing in order to reach the 1E35 level given for the effective target of the HL-LHC in terms of "virtual luminosity" as defined in the first section of this paper. Finally, in all cases, an efficient tool for luminosity leveling remains to be defined.

An upgrade scheme based on crab-cavities, if available and fully operational, would then bring an elegant solution for the above two problems, but still based on the ATS scheme in order to achieve a round collision optics with $\beta^* = 15$ cm. The aim of this section is however to develop and analyze a scenario without crab-cavity, in order to demonstrate that the ATS scheme is not only a necessary ingredient for any path towards to the LHC Upgrade but represents by itself a complete solution for the HL-LHC which is only based on the already existing and well-characterized LHC technology. The aim is therefore to develop a specific scenario

- relying on the generation of flat collision optics thanks to the ATS scheme,
- betting on a sizable (but not aggressive) reduction of the beam emittances, as suggested by the present behaviour of the LHC beam, in order to find the factor of about 2 missing in terms of "virtual performance",
- and using the crossing angle as a tool for luminosity leveling.

A possible optics and beam parameter set to reach this goal will be discussed in the next paragraph, both for the 25 ns and 50 ns bunch spacing. Using the crossing angle for luminosity leveling will then be analysed in terms of triplet aperture and beam-beam effects.

Bunch spacing [ns]	25	50
Longitudinal plane		
Number of bunches	2808	1404
Bunch charge [10^{11}]	1.8	3.0
Bunch length [cm]	6.0 (1.6 eV.s)	8.5 (3.2 eV.s)
IBS growth time [h]	~ 21	~ 25
Transverse plane		
$\gamma\epsilon[\mu\text{m}]$	2.75	
β^*_X (Xing) [cm]	30	
$\beta^*_{\parallel}$ (non-Xing) [cm]	7.5	
X-angle [μrad]	$955\ (27.2\,\sigma) \rightarrow 455\ (13.0\,\sigma)$	
IBS growth time [h]	~ 18	~ 22
Performance		
Time needed for 1 fb^{-1}	6h10min	6h30min

Table 4: *Possible parameter sets for an HL-LHC without crab-cavities.*

Target parameters for an HL-LHC without crab-cavities

Two possible parameter sets are given in Tab. 4 in order to reach the performance targets of the HL-LHC assuming a bunch spacing by 25 ns or 50 ns. The transverse parameters have been taken identical in the two cases, in terms of β^* (flat optics of Fig. 3), transverse normalised emittance (reduced by 1μm with respect to its nominal value) and dynamic range of the crossing angle for luminosity leveling. This range is limited on one side by the 150 mm aperture of the new triplet and, on the other side, by the long range beam-beam interactions (see later). Then playing with the bunch charge and the bunch length, the two cases can be made very similar in terms of IBS growth times (about 20 hours in the horizontal and longitudinal planes), beam-beam tune footprint combining both the head-on and parasitic beam-beam collisions (see later) but also in terms of performance.

The performance is qualified by the time needed in order to integrate a luminosity of $1\,\text{fb}^{-1}$. It is of the order of 6 to 6.5 hours in the two cases, with about half of this time during which the luminosity can be sustained at the $5E34$ level at the beginning of the physics coast (see Fig. 7). It is worst noting that the beam intensity obtained in the "25 ns" case exceed the ultimate threshold by only 5%. On the other hand, the longitudinal emittance shall be reduced to 1.6 eV.s which is however perfectly reachable with the nominal RF system of the LHC and seems to be sufficient for Landau damping if extrapolating to 7 TeV the single bunch measurements which already took place in the LHC, and assuming no additional requirements imposed in multi-bunch operation [18]. The situation is not drastically different in terms of current for the other case. The total beam intensity can only be reduced by 10% with respect to the ultimate current for the 50 ns case, in order

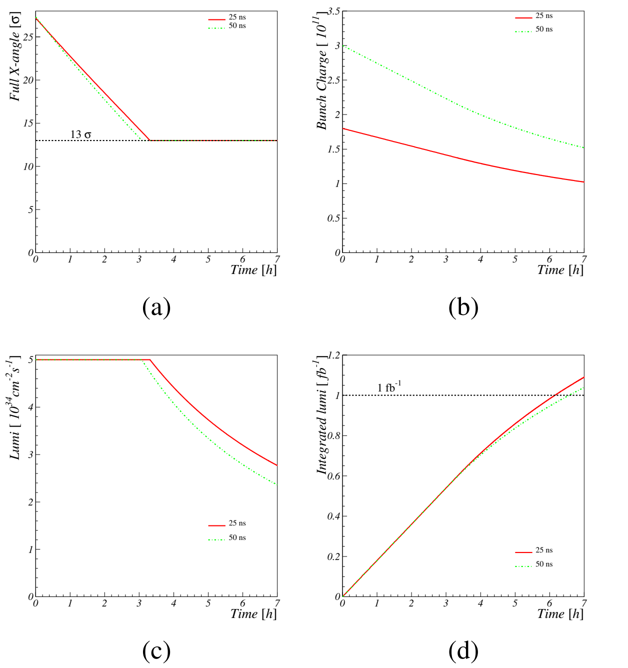

Figure 7: *Time evolution of the crossing angle (a), charge per bunch (b), instantaneous luminosity (c) and integrated performance (d) during an HL-LHC physics coast assuming the parameter sets given in Tab. 4 for a bunch spacing of 25 ns (solid lines) and 50 ns (dashed-dotted lines).*

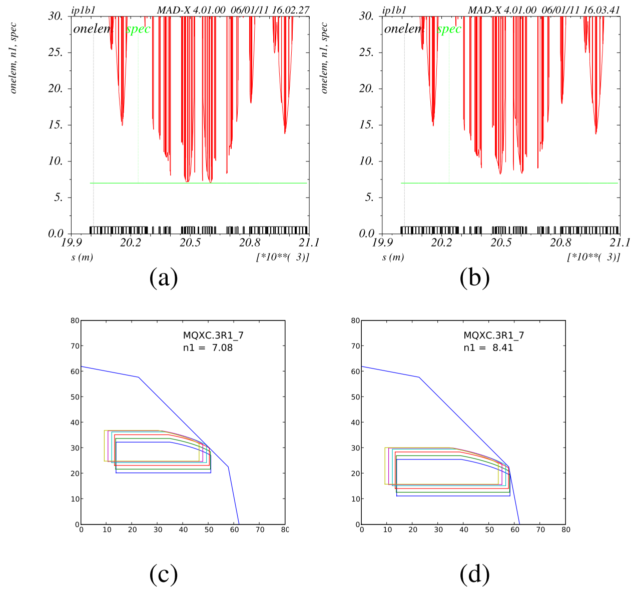

Figure 8: *Aperture plots of the low-β insertions (top) and extension of the secondary halo inside the octagonal beam-screen of Q3 (bottom) assuming the optics and the transverse emittance given in Tab. 4, and considering the initial and final crossing angle specified at the beginning (left) and end (right) of the physics coast.*

to stay competitive in terms of leveling time and beam life time (even if this case corresponds to a substantially larger "virtual luminosity" at the beginning of the coast).

The above estimates are based on the total hadron cross section of 100 mbarn per experiment, compared to 80 mbarn sometimes used by certain authors neglecting the elastic cross-section of 20 mbarn (see e.g. [5]). On the other hand the possible degradation of the performance due to IBS, estimated to about 10-15% in the worst case (see later), has not been taken into account because considered well inside the error bars related to the turn around time of the HL-LHC and therefore the number of $1\,\mathrm{fb}^{-1}$ fills which will be achievable in average per day at the horizon of 2020. On the other hand, in the presence of emittance growth due to IBS in the horizontal plane and emittance reduction in the vertical plane due to the radiation damping at 7TeV, a systematic luminosity unbalance is expected between the two experiments, assuming an alternated crossing scheme in IR1 and IR5 and the corresponding flat optics with $\beta^* = 30$ cm in the crossing plane. This unbalance should amount to about 10% (with the horizontal crossing configuration giving obviously the largest performance), and therefore around $300\,\mathrm{fb}^{-1}$ integrated over the full life time of the machine. This number is large enough to justify a full flexibility in the choice of the crossing angle for the HL-LHC collision optics, passing periodically from one crossing plane to another one in a given experiment, while always preserving an alternated crossing scheme for beam-beam related reasons. Sticking to the concept of an octagonal shape beam-screen to equip the new triplet (as developed for Phase I) is therefore more than justified in this case.

Luminosity leveling with crossing angle and impact on aperture and beam-beam tune footprint

Aperture. As already mentioned, using the crossing angle for luminosity leveling may be very demanding in terms of aperture, at least for round collision optics, i.e. with the same β^* in the two transverse planes. The situation is quite different when the β^* aspect ratio is substantially different from unity and the crossing plane corresponds to the plane of biggest β^* (i.e. smallest β^{max}). Using the parameter set proposed in the transverse plane in Tab. 4, in particular assuming a normalised emittance of only 2.75 μm, considering the new triplet, D1, D2, Q4 and Q5 discussed in the previous section, and applying the standard tolerance budget of the LHC in collision [19], the aperture plots of the new high luminosity insertion is showed in Fig. 8. The left and right pictures illustrate the situation at the beginning and the end of the coast, respectively, that is with an initial and final crossing angle of $27.2\,\sigma$ and $13\,\sigma$ imposed in the plane of biggest β^*. The sensitivity of the 2D normalised aperture with respect to the crossing angle is then rather moderate, corresponding to a variation of only $\delta n_1 \sim 1.3$ in the inner triplet for a modification of the crossing angle by almost $15\,\sigma$. When inspecting for instance the shape of the secondary halo inside the octagonal beam-screen of Q3.R, the reason is simple and lies in the fact that the aperture requirements are mainly driven by the plane of smaller β^*, that is the plane perpendicular to the crossing plane (see Fig.'s 8(c) and (d)).

Finally, compared to a luminosity leveling technique based on β^*, using the crossing angle goes exactly in the opposite (and in the right) direction, relaxing the aperture requirements and therefore offering a certain budget for emittance growth during the luminosity production.

Beam-beam tune footprint. The situation in terms of beam-beam tune footprint is illustrated in Fig. 9, assuming the two possible parameter sets proposed in Tab. 4 (25 ns and 50 ns), neglecting the possible contributions of IR2 and IR8 and assuming 21 long range interactions on either sides of the new high luminosity insertions. The two cases shows a very similar behaviour, both at the beginning of the physics coast (Fig. 9(a)) where the beam-beam tune footprint is very small due to the very large crossing angle, but also just before the second part of the coast when the normalised crossing angle has just reached $13\,\sigma$ and the beam current is still rather high ($N_b \approx 1.4/2.2E11$ for the 25 ns and 50 ns case, respectively). While, in both cases, the total tune spread does not exceed the 0.01 (design) limit of the nominal LHC, two phenomenons can be clearly observed:

- the development of wings in the tune footprint due to the long-range beam-beam interactions, pushing some particles towards the coupling resonance (more precisely the (2,-2) resonance), especially for the 25 ns case,
- a sizable tune shift of the order of $\Delta Q_{LR} \approx -0.01$ in both planes. This effect adds up with the head-on beam-beam tune shift and comes from the fact that, for flat optics, an alternated crossing scheme can only warrant a partial compensation of the long-range beam-beam tune shift between IR1 and IR5.

A dynamic readjustment of the betatron tunes looks then mandatory during the leveling period. However, considering also the so-called pacman bunches which sample only half of the long-range interactions in the worst case, only half of the effect shall actually be corrected. This would therefore correspond to a tune correction of the order of

$$\Delta Q = -\Delta Q_{LR}/2 \approx 0.005\,. \qquad (8)$$

This tune correction is not included in Fig. 9(b) but will definitely contribute to shift the overall footprint just above the 10$^{\text{th}}$ but still well below the 3$^{\text{rd}}$ order resonances (i.e. $0.3 \leq Q_x < Q_y \lesssim 0.32$), which was a fundamental criteria for the choice of the nominal working point of the LHC (see e.g. [20]).

CONCLUSIONS AND OUTLOOKS

The Achromatic Telescopic Squeezing (ATS) scheme clearly opens a new β^* territory. It can squeeze by a factor of up to 4 the hard limit of $\beta^* \sim 30$ cm (resp. ~ 25 cm)

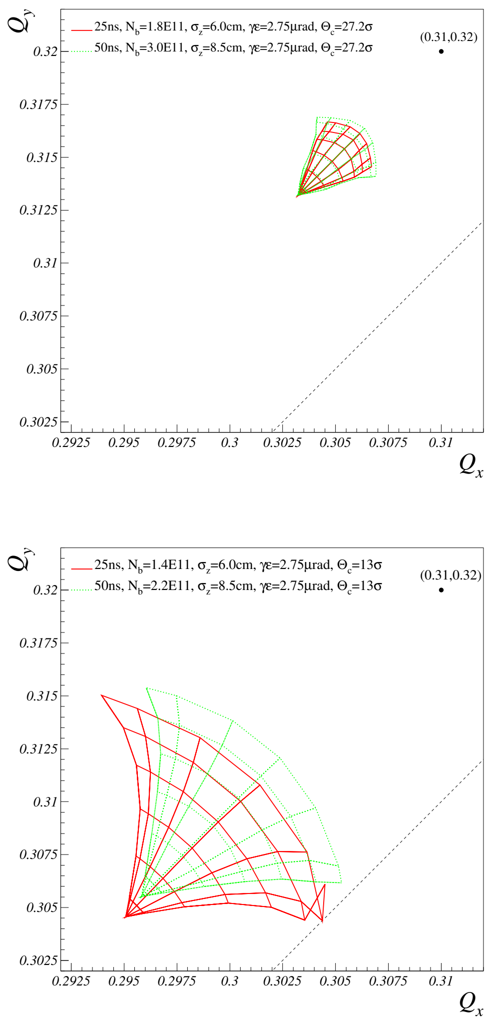

Figure 9: *Beam-beam tune footprint for particles with betatron amplitudes up to $6\,\sigma$, calculated at the beginning of the first (top) and second (bottom) period of the physics coast and based on the parameter sets defined in Tab. 4. The solid and dotted-dashed lines stand for a bunch spacing of 25 ns and 50 ns, respectively. The possible degradation due to head-on collisions at IP2 and IP8 is neglected. The number of parasitic encounters is assumed to be 21 on either side of IP1 and IP5. Only the case of nominal bunches is illustrated. The tune correction by $\Delta Q = +0.005$ is not included in the bottom picture (see Eq. 8).*

which was identified in the context of the Phase I Upgrade Project for an Nb-Ti (resp. Nb3Sn) triplet with an optimum aperture of 120 mm [2]. On the other hand, for more than one decade, the scenarios proposed for the LHC Upgrade heavily relied on a β^* lower or much lower than 25 cm (see e.g. [21] for a review), or just equal to 25 cm for the most aggressive ones in terms of technology (crab-cavity, Nb3Sn triplet) and/or beam parameters (in particular bunch charge). In this respect, the ATS scheme shall then be considered as a fundamental basis for the HL-LHC project (formerly the LHC Upgrade Phase II) since it is the only optics scheme available today which enables to reach such low values of β^*.

Furthermore, by pushing so widely the β^* limits, the ATS scheme opens the route for flat collision optics, that is with a very small β^* in the plane perpendicular to the crossing plane. Flat optics shall be seen as a compromise in terms of luminosity gain at low β^*, with a gain with $1/\sqrt{\beta^*}$ without crab-cavity, which ranges exactly in between a quick saturation of the luminosity for round optics and a gain with $1/\beta^*$ assuming the availability of crab-cavities. Said differently, the ATS scheme is therefore not only a necessary ingredient for any upgrade scenario but represents by itself a novel path towards the LHC Upgrade, if used to produce flat collision optics, and therefore relying only on already existing and well-characterized technologies.

As described in details in the paper, the ATS scheme in its present stage requires however to be further optimized in order to mitigate its impact onto the dynamic aperture of the ring in collision, but the direction to follow is rather clear. In addition, contrary to any existing upgrade proposal, the ATS scheme can also be directly tested in the LHC, at least in its basic principles, and in order to analyze its limits for instance in terms of maximum allowable peak β-functions in the arcs or robustness of its fundamental chromatic properties (off-momentum β-beating, non-linear chromaticity, spurious dispersion induced by the crossing angle). One can also easily imagine that if the transverse emittance of the LHC beam is kept as small as it is found today, certain performance limitations related to the chromatic aberrations induced at low β^* may well be reached before saturating the aperture of the existing triplet. This scenario would then be at the extreme opposite of the one which motivated the Phase I project, but corresponds more or less to the present situation of the RHIC machine. In this configuration, the ATS scheme would then offer as well a efficient mean to boost the performance of the machine, at least after the long shut-down, that is after reaching an energy of 6.5-7 TeV per beam. In this case, indeed, assuming a normalised emittance of $\gamma\epsilon \sim 2.5\mu$m, a β^* of let say 35 cm would be easily achievable thank to the ATS scheme, while being fully compatible with the aperture of the existing triplet.

Finally, at a given beam brilliance, the ATS scheme is clearly in favor of a low emittance rather than a high intensity beam. The intrinsic optics limitations of the scheme are indeed only driven by mechanical and dynamic aperture related constraints. Furthermore a substantial margin exists for the head-on beam-beam tune shift due to the increase of the Piwinski angle at low β^*, even at ultimate intensity and nominal emittance, and still considering a beam-beam limit of $\Delta Q_{ho}=0.01$ for the LHC. From the point of view of the author, the last big unknown is then related to the eventual excitation of beam-beam driven synchro-betatron resonances, operating with a Piwinski angle equal, larger or much larger than 1 (which is far from being recommended in [22]) and/or due to the hour-glass effect at low β^*. This question concerns most of the upgrade scenarios and is even more relevant for the HL-LHC since one of the key-stones of the project is based on luminosity leveling trough aggressive variations of the Piwinski angle (via crab-cavities, β^* or the crossing-angle itself). This recurrent question should therefore be answered with high priority since the output of such an analysis could drastically modify our present views and strategies for the LHC upgrade, i.e. pushing more on the bunch length side, with more RF voltage and Landau cavities, than on the β^* side.

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