AN ACHROMATIC TELESCOPE SQUEEZING (ATS) SCHEME FOR THE LHC UPGRADE

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Abstract

A novel optics concept has been invented and developed in the context of the LHC Upgrade studies. It offers an incredibly powerful and flexible machinery in order to squeeze β^* in a symmetric or asymmetric way (so-called "round" or "flat" optics, respectively), while perfectly controlling the chromatic aberrations induced (off-momentum beta-beating, non-linear chromaticity, spurious dispersion due to the crossing angles). The basic principles of the scheme are described and a specific path for the LHC upgrade is built accordingly, only relying on the existing and well-characterized LHC-like technology, and based on the production of flat collision optics with very small β^* (7.5 cm) in the plane perpendicular to the crossing plane.

INTRODUCTION AND MOTIVATIONS

One key ingredient to push the performance of a collider is the reduction of the transverse beam sizes at the interaction point (IP), which are directly given by the transverse beam emittances 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 chain for the emittance and by a series of optics and aperture-related constraints for β^* in the collider itself. Indeed, provided the inner triplet (IT) is equipped with new low-β quadrupoles of sufficiently large aperture, severe optics limitations coming from the "non-IT side" of the machine have been identified in the context of the so-called Phase I Upgrade project [1]. While of different nature, all these limitations can be quantified by the maximum possible peak β-function that is reached in the inner triplet, namely β_{max}, and can be matched to the regular optics of the arcs, within the aperture and the gradient limits of the insertion magnets, while ensuring the correct-ability of the chromatic aberrations induced without exceeding the available strength of the lattice sextupoles. As summarized in Tab. 1, these limitations were given by

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

THE ATS SCHEME

Concerning the first limitation, the only solution is to equip the LHC matching sections with new two-in-one magnets of larger aperture. Concerning the poor optics flexibility observed at low β^* in the experimental insertions IR1 and IR5, with some quadrupoles being pushed to very low or very high gradients in the matching section

Table 1: Optics limitations for the LHC Upgrade Phase I, expressed in terms of maximum possible peak β-function reached in the inner triplet and corresponding minimum possible β^* for a Nb-Ti triplet [1]. At constant β_{max}, and therefore IT aperture, these β^* limits can be pushed down by about 25% assuming a 50% stronger Nb_3Sn triplet.

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

and dispersion suppressor, respectively, one possibility is to allow floating matching conditions at the boundaries of these two insertions. 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 are generated 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 sextupole, i.e. at the sextupoles belonging 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.

This novel approach is particularly well-suited to the LHC for the two following reasons. First, due to the large dynamic range of the machine in energy, from 450 GeV to 7 TeV, and the reduction in proportion of the transverse emittances during the ramp, the peak β-functions in the arcs can be increased by a factor of about 16 at top energy without exceeding any aperture-related limits. Then, 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 maintained during the whole LHC cycle. Therefore all the ingredients are already available in the existing machine to blow up the β-functions in the arcs 81/12/45/56 at 7 TeV and then implement the principle of this so-called Achromatic Telescopic Squeezing (ATS) scheme.

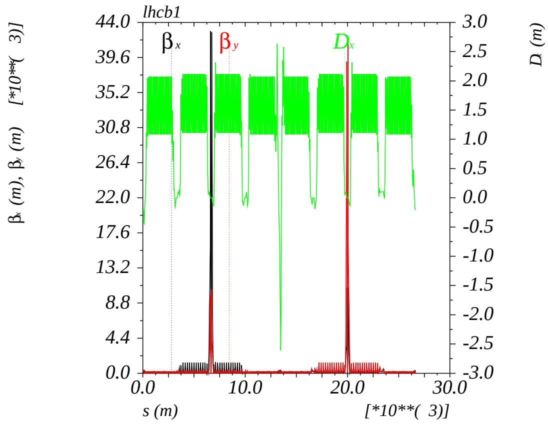

Figure 1: Alternated flat collision optics with $\beta^*_{x,y} = 7.5/30$ cm at IP1 and $\beta^*_{x,y} = 30/7.5$ cm at IP5. Starting from a pre-squeezed optics with $\beta^*_{x,y} = 60$ cm, β-beating waves are induced in sectors 81, 12, 45 and 56 with peak values increased by a factor of 2 or 8 with respect to the regular FODO optics.

A comprehensive description of the scheme can be found in [2], in particular concerning the phase constraints imposed on the left and right side of the low-β insertions, and the optics squeeze which is achieved 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 [3]. A flat collision optics is then illustrated in Fig. 1 with $\beta^* = 30$ cm in the crossing plane, and β^* squeezed down to the r.m.s. bunch length, i.e. 7.5 cm for the LHC beam, in the other plane. In this particular case, it is assumed that the plane of smallest β^* together with the crossing plane, which is perpendicular, are 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. However any other possible combination has been successfully rematched and a round collision optics with $\beta^* = 15$ cm at IP1 and IP5 can also be built in a similar way, which would be more appropriate assuming the availability of crab-cavities [4]. Within the exception of the Q5 quadrupoles of IR6 which needs to be made 25% longer, and heavier interventions obviously needed in the matching section and inner triplet of IR1 and IR5, installing magnets of larger aperture (see [2] for more details), all these optics have been found fully compatible with the existing hardware and layout of the LHC.

The chromatic properties of the ATS scheme are illustrated in Fig. 2 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

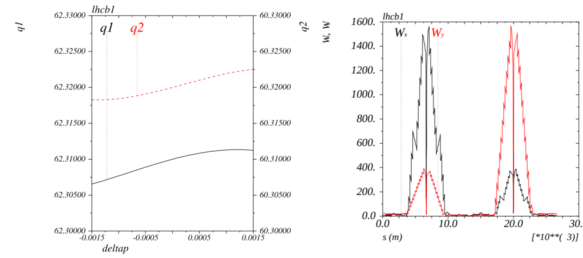

Figure 2: Chromatic variation of the betatron tunes (left) and Montague functions along the machine starting from IP7 (right) for the flat collision optics showed in Fig. 1.

collimation insertions IR3 and IR7 and at IP1 and IP5. Another important feature 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 and which 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 by the ATS scheme, 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 correct it to a level of ~ 50 cm in the inner triplet (see [2] for more details).

REACHING THE HL-LHC PERFORMANCE TARGETS

At the horizon 2020-2022, the LHC should be able to deliver an integrated luminosity of about 250 fb^{-1} per year, that is about 1 fb^{-1} per fill. This target sets the scene of the HL-LHC Upgrade Project [6], which bases its strategy on an instantaneous luminosity leveled to 5.0×10^{34} cm^{2}s^{-1}. Such a high luminosity, even sustained during a couple of hours per fill, obviously assumes that more, typically a factor of 2 more, is available in the machine, even if not usable due to limitations on the detector side (e.g. in terms of pile-up events per bunch crossing) or on the machine side. Assuming the so-called ultimate parameters of the LHC beams (2808 bunches with 1.7×10^{11} ppb, $\gamma\epsilon = 3.75\,\mu$m and $\sigma_z = 7.5$ cm), the ATS scheme can deliver a peak luminosity of 5.6×10^{34} for a flat collision optics pushed to $\beta^*_{x/y} = 7.5/30$ cm. Roughly speaking, a factor of approximately 2 is then still missing to reach the effective target of the HL-LHC. Finally, in all cases, an efficient tool for luminosity leveling remains to be defined. The aim is therefore to develop a specific scenario 1) relying on the generation

Table 2: Parameters of an HL-LHC without crab-cavities.

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 eVs)	8.5 (3.2 eVs)
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]	$955\ (27.2\,\sigma) \to 455\ (13.0\,\sigma)$	
IBS growth time [h]	~ 18	~ 22
Performance per experiment (for a total hadron cross-section of 200 mbarn for the 2 experiments)		
Time needed for 1 fb^{-1}	6h10min	6h30min

of flat collision optics thanks to the ATS scheme, 2) 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 2 missing above, 3) using the crossing angle as a tool for luminosity leveling.

Tab. 2 gives two possible optics and beam parameter lists in order to reach this goal, for bunches spaced by 25 ns or 50 ns, and using the crossing angle in the plane of larger β^* for luminosity leveling. The transverse parameters have been taken identical in the two cases, in terms of β^* (flat optics of Fig. 1), 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 assumed for the new triplet and, on the other side, by the long-range beam-beam interactions. 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 terms of beam-beam tune footprint (see [5] for more details) 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 level of 5.0×10^{34} cm^2s^{-1} (see Fig. 3).

CONCLUSIONS AND OUTLOOK

The Achromatic Telescopic Squeezing (ATS) scheme can squeeze by a factor of up to 4 the hard limit of $\beta^* \sim$ 30 cm (resp. $\sim$ 25 cm) which was identified in the context of the Phase I Upgrade Project for a Nb-Ti (resp. Nb_3Sn) triplet with an optimum aperture of 120 mm [1]. It brings therefore a touch of realism to the parameter lists developed so far for the LHC Upgrade, all of them already counting on a β^* smaller or much smaller than 30 cm (see e.g. [7] for a complete review). Furthermore, by pushing so strongly the

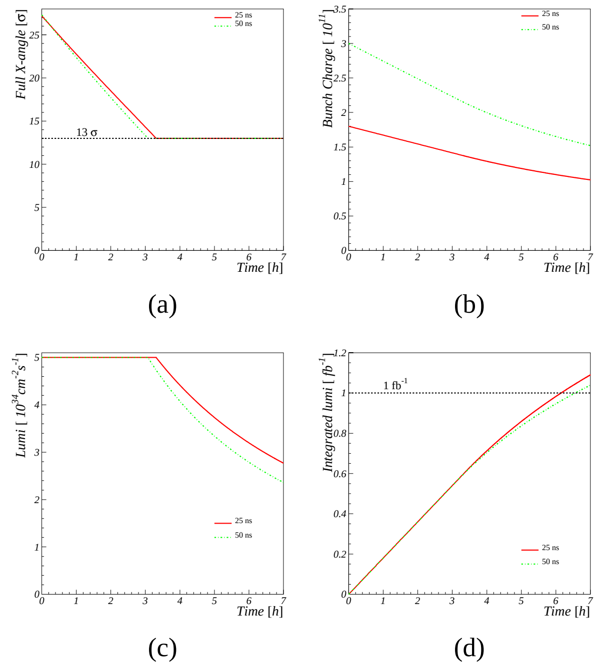

Figure 3: Time evolution of the crossing angle (a), charge per bunch (b), instantaneous luminosity (c) and integrated performance (d) during an HL-LHC physics coast assuming the parameter list given in Tab. 2 for a bunch spacing of 25 ns (red solid lines) and 50 ns (green dashed lines).

β^* limits, the ATS scheme opens the route to flat collision optics, i.e. 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 in itself a novel path towards the LHC Upgrade, with flat collision optics which only relies on already existing and well-characterized technologies.

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