OPTICS AND LAYOUT SOLUTIONS FOR HL-LHC WITH LARGE APERTURE NB3SN AND NB-TI INNER TRIPLETS*

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Abstract

The LHC Upgrade studies, formalized into the High-Luminosity LHC (HL-LHC) project, relies on the feasibility of very low β^*, and in particular on a novel achromatic squeezing mechanism, the ATS scheme [1] which is presently under test in the LHC. We present two optics and layout scenarios for the HL-LHC using the ATS scheme, one based on Nb_3Sn triplet quadrupoles with a coil aperture compatible with an operational gradient of 150 T/m, and a backup scenario based on the NbTi technology compatible with an operational gradient of 100 T/m. The solution obtained are analyzed in terms of β^* reach (flat or round), mechanical acceptance, optics flexibility, chromatic properties, and dynamic aperture in the presence of the large β-beating waves induced in the arcs by the ATS scheme.

INTRODUCTION

The High-Luminosity LHC project (HL-LHC [2]) relies on a strong reduction of β^* at the interaction points of the ATLAS and CMS experiments, IP1 and IP5 respectively. New magnets of larger aperture are foreseen in the interaction region (IR) to be compatible with this rather aggressive β^*. A novel squeezing mechanism (ATS [1]) is also foreseen to preserve the optics flexibility and guaranty the correct-ability of the chromatic aberrations when reducing β^*, at the cost of moderate operational complications and small dynamic aperture degradations. In the following we present two layouts, the HL-LHC baseline relying on a Nb_3Sn inner triplet (IT) quadrupoles, and a second one still based on the NbTi technology.

LAYOUT AND OPTICS

The region in the range of ± 200 m left and right of IP1 and IP5 will be completely dismantled. The various equipment supposed to be replaced and new ones are listed in Table 2. The layout of the inner triplets (see Table 1) is optimized to minimize the peak beta functions, while optimizing the match-ability of the optics to the arcs for the so-called ATS pre-squeezed optics of intermediate β^* (see [3] for more details). The IT layout is obviously different for the two technologies, taking into account an improvement of the critical field by about 50% for the Nb_3Sn technology and therefore of the maximum possible gradient at constant aperture. For both options, the optics are based on the ATS scheme and built onto the experience of previous works, in particular the SLHCV3.0 version of the SLHC optics and layout [4]. Table 3 shows the optics configurations developed accordingly for a Nb_3Sn and NbTi triplet operating at 150 T/m and 100 T/m, respectively [5].

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Table 1: Triplet and MS Layout for the Two Technologies

Name	Nb_3Sn	NbTi
Q1,Q2,Q3 max gradient	150 T/m	100 T/m
Q1, Q3 length	7.685 m	10.629 m
Q2a, Q2b length	6.577 m	8.695 m
Q1, Q2a distance	3.560 m	3.560 m
Q2a, Q2b distance	1.915 m	1.915 m
Q2b, Q3b distance	3.560 m	3.560 m
D2 shift towards the IP	11 m	11 m
Q5 shift towards the arcs	11 m	14 m

For the Nb_3Sn case, two possible injection optics are considered, one corresponding to the nominal LHC injection optics with $\beta^* = 11$ m, and a second one with $\beta^* = 5.5$ m which has the advantages of smaller β functions at Q5 and Q6, and a reduction by a factor of 2 of the dynamic range of the squeeze. The so-called pre-squeezed optics at $\beta^* = 40$ cm is similar to a standard LHC collision optics, that is using exclusively the matching quadrupoles of the low-β insertion, but is matched with specific left and right phase advances that allow an efficient compensation of the off-momentum beta beating induced by the triplet [3]. These additional matching conditions limit substantially the minimum possible pre-squeezed β^*, but still at a level which is less or equal to the chromatic limit related to the maximum strength of the arc sextupoles participating to the IT chromatic correction (one sector of sextupole per triplet). As soon as the pre-squeezed β^* limit is reached, the squeeze can continue acting on the matching quadrupoles of the insertions on either side of IR1 and IR5, at constant settings in the low-β insertion proper and in the sextupoles [3]. Two squeezed optics, with $\beta^* = 15$cm and 10 cm in both planes, have been generated accordingly. They are compatible with a triplet aperture of 140 mm and 150 mm, respectively, with in addition a reduction of the aperture margins in the second case (see later). These optics fully rely on crab cavities to make an efficient use of the strong reduction of β^* w.r.t. its nominal value of 55 cm for the LHC. Four flat collision optics, with a β^* aspect ratio of 4 are also available, with even smaller β^* in the plane perpendicular to the crossing plane. A β^* aspect ratio of 4 is found to be optimal for the IT aperture in the presence of a crossing angle of the order of 12-15 σ. Flat optics are indeed considered as a possible backup option in order to preserve the HL-LHC performance in the absence of crab-cavities [3].

For NbTi triplet quadrupoles operating at 100 T/m, the

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Table 2: New Beam Line Elements in IR1 and IR5

Name	Type	Changes with respect the LHC as built
TAS	Absorber	60 mm aperture instead of 34 mm
Q1, Q3	Quadrupole	140 (150) mm aperture (instead of 70 mm), longer, weaker (see Tab. 1 for details)
Q2a, Q2b	Quadrupole	as above and hosted in separated cryostats
MCBXD	Corrector	nested H and V orbit correctors (1.8 T.m) on the IP-side of Q2a and non-IP side of Q2b
MCBXC	Corrector	stronger nested H and V orbit corrector (4.5 T.m) on the non-IP side of Q3
MQSX	Corrector	a2 corrector in between Q3 and D1 (performance specification still missing)
MCSTX	Corrector	nested b3, b6 coils in between Q3 and D1 (performance specification still missing)
MCOSSX	Corrector	nested a3, a4, b4 coils in between Q3 and D1 (performance specification still missing)
MCDTSX	Corrector	nested a5, b5, a6 coils in between Q3 and D1 (performance specification still missing)
D1	Dipole	6.5 m long, 40 T.m, same aperture as the triplet (cold magnet instead of 6 warm modules)
TAN	Absorber	2-in-1, 145 mm aperture separation, elliptical aperture (41,37) mm instead of (26,26) mm
D2	Dipole	10m long, 40 T.m, 2-in-1, 186 mm aperture separation, 105 mm aperture (instead of 80 mm)
MCBRD	Corrector	2-in-1, H (or V) strong orbit corrector (7 T.m) on the non-IP side of D2
ACRAB	RF deflector	3 modules offering a 10MV deflecting voltage per beam per IP side
Q4	Quadrupole	2-in-1, 90mm aperture (instead of 70 mm), 160 T/m × 3.2 m
Q5	Quadrupole	2-in-1, 70mm aperture (instead of 56 mm), 160 T/m × 4.8 m (longer version of the existing Q4)

Table 3: Optics Configuration Available in the SLHCV3.1 Repository for the 150 T/m and 100 T/m Triplet Options [5].

name	$\beta^*_\times$ [m]	$\beta^*_\parallel$ [m]	$\theta_\times/2$ [μrad]	$\Delta_\parallel/2$ [mm]	$\times_{\rm plane}$ IP1/5
150 T/m triplets					
injection	11.0	11.0	170	2	any
injection	5.5	5.5	245	2	any
pre-squeeze	2.0	2.0	80	2	any
pre-squeeze	0.40	0.40	180	0.75	any
squeeze	0.15	0.15	295	0.75	any
squeeze	0.10	0.10	360	0.75	any
squeeze	0.30	0.075	275	0.75	v/h
squeeze	0.20	0.05	335	0.75	v/h
squeeze	0.30	0.075	275	0.75	h/v
squeeze	0.20	0.05	335	0.75	h/v
100 T/m triplets					
pre-squeeze	0.50	0.50	150	0.75	any
squeeze	0.19	0.19	235	0.75	any
squeeze	0.125	0.125	305	0.75	any
squeeze	0.335	0.100	250	0.75	v/h
squeeze	0.25	0.0625	270	0.75	v/h
squeeze	0.335	0.100	250	0.75	h/v
squeeze	0.25	0.0625	270	0.75	h/v

pre-squeezed β^* needs to be increased up to 50 cm in order to stay compatible with the chromatic limit previously mentioned. Even with this relaxed β^*, the optics flexibility is substantially reduced compared to the previous case (e.g. Q4/Q5 left/right antisymmetry not strictly respected), indicating that the length of the triplet assembly starts to be a limiting factor. For the squeezed optics, β^* shall then be re-increased in the same proportion, i.e. by 20-25% compared to the Nb_3Sn case, while leading to the same aperture requirements for the new HL-LHC magnets (inner triplet and matching section, see Table 2).

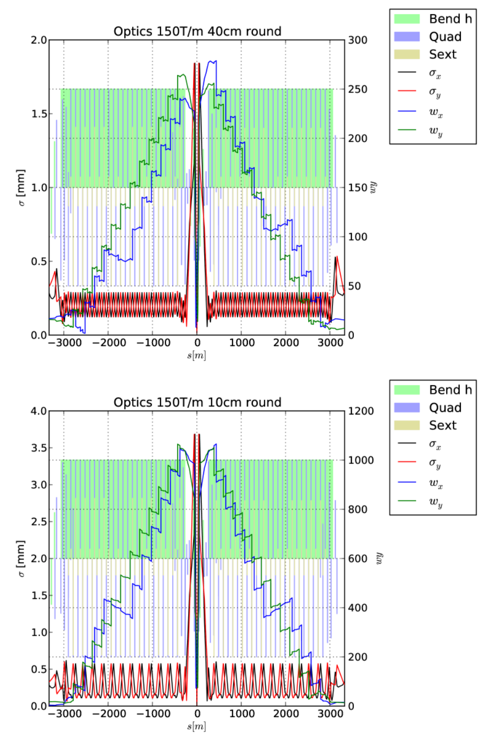

Figure 1: Nb_3Sn IT case: optics and Montague functions from IP4 to IP6 for $\beta^* = 40$ cm (top) and 10 cm (bottom).

MECHANICAL ACCEPTANCE

The mechanical acceptance of the new layout has been evaluated, assuming no specific budget for the beam related tolerances (closed orbit, β-beating,...), but considering mechanical tolerances of the same order as the ones used for the existing LHC magnets. Under these conditions, an extrapolation at 7 TeV of the present LHC operation suggests that one needs a normalized aperture of about 14σ (using a normalized emittance of a 3.5 mm mrad) in order to accommodate the various collimation and protection devices, with sufficient margin between them [6].

The normalised aperture of the triplet and D1 is estimated using three models: a) an octagonal beam screen and no shielding, b) a circular aperture with a 5 mm thick liner for shielding and no beam screen, c) as before but with a coil aperture increased to 150 mm. The aperture of D2 and Q4 are modeled by a rectellipse beam screen with the respective dimensions of (37,42) mm and (30,35) mm for the gap and radius. These dimensions are a priori compatible with a coil aperture of 105mm for D2 and 90mm for Q4. In addition the two bores of D2 are assumed to be separated by 186 mm, while the aperture separation of Q4 is nominal (194 mm). The results in Table 4 and Fig 2 shows that $\beta^* = 15$ cm (or 19 cm for the NbTi case) is compatible with the triplet coil aperture of 140 mm but no beam screen or no shielding, while $\beta^* = 10$ cm (or 12.5 cm for the NbTi case) can be reached only if the cleaning and protection systems can cope with a beam stay clear of about $11 - 11.5\sigma$ and the IT aperture is pushed up by 10 mm. The aperture of D1, not shown in the Table 4, are consistently larger by $0.5 - 1\sigma$ compared to the triplet. However, while for the triplet trading the absence of the beam screen is justified, an increase of the D1 aperture to fit a beam screen might be required in order to reduce the cryogenic load at 1.9K.

Table 4: Minimum Mechanical Aperture in the Triplet per Class of Magnets Given in Units of σ.

β^* [mm]	MQX a)	MQX b)	MQX c)	D2	Q4
		150 T/m triplets			
150 150	13.2	13.7	15.2	21.6	23.3
75 300	12.5	13.0	14.1	16.3	16.5
100 100	9.8	10.2	11.4	17.3	19.0
50 200	10.2	10.6	11.5	13.3	13.5
		100 T/m triplets			
190 190	13.4	13.9	15.4	20.2	24.2
100 335	12.7	13.2	14.3	15.7	17.6
125 125	9.6	10.0	11.2	16.0	19.6
62.5 250	10.0	10.4	11.3	12.4	13.9

DYNAMIC APERTURE

The dynamic aperture (DA) of the LHC in collision is generally dominated by the beam-beam effects, the field quality of the inner triplet, and very weakly affected by the field imperfections of the arc magnets. For the ATS optics this hierarchy should be preserved, in particular in the presence of the higher beta functions in 4 of the LHC 8 arcs and proportional to $1/\beta^*$. It is therefore useful to characterize the DA without including the field quality of the magnets in the low-β regions. For all the optics considered in the 150 T/m cases, the results show a strong DA reduction with the decrease of β^* but still an acceptable DA of more than 11σ in the worst case (see Tab. 5). The results obtained in the 100 T/m case are very similar but, as before, modulo a β^* increase by 20-25%.

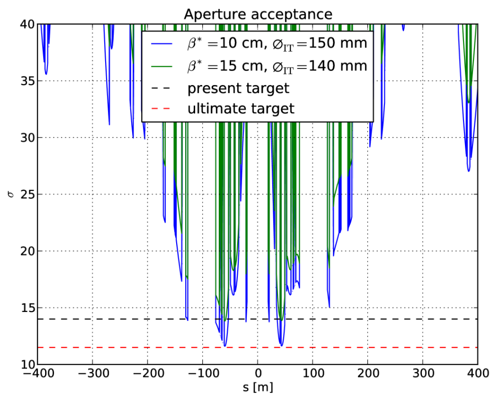

Figure 2: Mechanical acceptance of the new low-β insertion for two optics and aperture options.

Table 5: 10^5 Turns Dynamic Aperture in Units of Sigma for the 150T/m Optics with the Field Imperfections with Field Imperfection in the Arcs Only

β^* [mm]	15°	30°	45°	60°	75°
400 400	39.28	40.41	39.46	39.11	39.56
150 150	23.27	26.04	22.53	21.54	20.85
75 300	16.20	16.97	16.99	18.11	16.79
100 100	15.44	17.58	14.49	14.20	13.68
50 200	11.30	11.01	11.97	12.10	11.29

CONCLUSION

The 150 T/m Nb_3Sn option combined with the ATS scheme represents a solid baseline for the HL-LHC in terms of optics flexibility and dynamic aperture. The β^* reach is limited by the triplet aperture. Pushing to 150 mm the IT aperture, and assuming no beam-screen (but shielding) combined with some upgrade of the collimation system might allow to reach $\beta^* = 10$ cm. The 100 T/m NbTi option offers reduced performance, but only 20-25% less in β^*, due to the weaker gradient and longer triplet, although it is worth noting that the optics flexibility starts to become a limiting factor, which might justify deeper modifications in the layout of the matching section.

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