PARAMETRIC STUDY OF OPTICS OPTIONS FOR THE HL-LHC PROJECT*

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Abstract

The LHC Upgrade studies have been recently formalized into the High-Luminosity LHC (HL-LHC) project. The paper explores the parameter space in terms minimum β^* (flat and round), and luminosity leveling scenarios, constrained by the triplet gradient and aperture and still compatible with optics solutions based on the ATS scheme [1]. The limitations of the proposed solutions, essentially given by the preservation of the dynamic aperture in the presence of large beta-beating waves induced in the arcs by the squeezing scheme are investigated. The results will be combined in scaling laws benchmarked with existing fully developed scenarios.

INTRODUCTION

The HL-LHC project [2] relies on a smaller β^* than presently possible at the interaction point of the ATLAS and CMS detector, IP1 and IP5 respectively. A redesign of the final focus system and new squeeze optics are therefore necessary. For a triplet design that aims at minimizing β^* a tradeoff has to be found between quadrupole apertures, which maximize the β^* reach [3], and quadrupole lengths, chromatic and geometric aberrations, optics flexibility, which limit β^*. The ATS scheme pushes the chromatic aberration limits further with respect to nominal-like optics allowing smaller β^* at a modest cost of additional geometrical aberrations and optics flexibility loss.

TRIPLET OPTICS

The peak beta function ($\beta_{\rm max}$) in the triplet quadrupoles (Q1, Q2, Q3) is the limiting factor of a triplet design. $\beta_{\rm max}$ is minimized when the peak beta function in the focusing plane of Q2 ($\beta_{\rm Q2}$) and the one of the focusing plane of Q3 ($\beta_{\rm Q3}$) are equal and the gradients of Q1, Q2, Q3 ($g_{\rm Q1}, g_{\rm Q2}, g_{\rm Q3}$) are all equal to their maximum values [3]. The aperture of Q2 and Q3 can be the same while Q1 could have a smaller aperture and larger gradient. The drift between quadrupole should be minimized. In this configuration free variables are the length of Q1, Q2, Q3 ($l_{\rm Q1}, l_{\rm Q2}, l_{\rm Q3}$) that can be used to control the $\alpha_{x,y}$ at the end of Q3. The fine control of this boundary condition is necessary to optimize the optics flexibility of the matching section. For the HL-LHC triplets, the optimization strategy slightly differs from the ideal case and it is described in the following paragraph.

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Table 1: Layout and optics of the triplets as a function of gradient for a reference β^* of 60 cm.

		$g_{\rm Q2}$ [T/m]			
		100.00	118.00	150.00	170.00
β_{Q2a}	[m]	6183	5457	4750	4371
β_{Q2b}	[m]	6296	5547	4849	4450
β_{Q3}	[m]	6296	5546	4850	4451
$g_{\rm Q1}$	[T/m]	100.00	118.00	149.40	165.77
$g_{\rm Q2}$	[T/m]	100.00	118.00	150.00	170.00
$g_{\rm Q3}$	[T/m]	97.00	116.98	150.00	170.00
$l_{\rm Q1}$	[m]	10.629	9.465	7.685	7.206
$l_{\rm Q2a/b}$	[m]	8.695	7.970	6.577	6.184
$l_{\rm Q3}$	[m]	10.629	9.465	7.685	7.206
d_{12}	[m]	3.560	3.050	3.560	3.050
d_{22}	[m]	1.915	1.640	1.915	1.640
d_{23}	[m]	3.560	3.050	3.560	3.050
$l_{\Sigma\rm l_Q}$	[m]	38.648	34.870	28.524	26.780
$l_{\rm total}$	[m]	47.683	42.610	37.559	34.520
$\beta_{x,Q4}$	[m]	828	651	591	509
$\beta_{y,Q4}$	[m]	956	890	818	755
$\alpha_{x,Q4}$		15.28	12.46	10.47	9.20
$\alpha_{y,Q4}$		5.36	4.68	4.12	3.80

All triplet quadrupoles have the same aperture and the same maximum gradient in order to require one single magnet cross section design. $l_{\rm Q1} = l_{\rm Q3}$ in order to reduce the number of spares. Anyway it has been checked that dropping this condition leads to marginal gains. $l_{\rm Q1}$ is used as free variable. Q2 is split in two elements since it would otherwise be too long. $l_{\rm Q2}$ is the second free variable and it is generally smaller than $l_{\rm Q1}$. The third free variable is either $g_{\rm Q1}$ or $g_{\rm Q3}$ depending on which one yields lower $\beta_{\rm max}$. The drift lengths between the quadrupoles (d_{12} distance from Q1 to Q2a, d_{22} distance from Q2a to Q2b, d_{23} distance from Q2b to Q3) are driven by hardware considerations and have been arbitrarily chosen ($d_{12} = d_{23} = 3.05$ m, $d_{22} = 1.64$ m) to be the same of the Phase I project [4]. This is justified for triplets of 120 mm aperture. In case of larger apertures, these values have been rescaled linearly with the aperture to take into account the impact of the coil ends. Since the layout optimization does not depend on β^*, but only on the gradient, a reference value of 60 cm has been chosen. The α boundary conditions have been translated in the β values at 165 m from the IP ($\beta_{x,\rm Q4}, \beta_{y,\rm Q4}$) which is about the location of the first matching quadrupole. These boundary

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Table 2: Limits on β^* reach without ATS but with chromatic beating correction (one arc per triplet) as a function of the triplet gradient. The last rows quantify the additional constraints included in the matching of the optics at $\beta^*_{\rm opt}$ and give an indication of the optics flexibility.

		gradient [T/m]			
		100	118	150	170
$\beta^*_{\rm chrom}$ limit	[cm]	49	45	40	38
$\beta^*_{\rm opt}$ limit	[cm]	50	43	40	37
Max Q7 strength	%	99.7	99	99.8	99
Min Q5,6 strength	%	12	8	8	12
Max trim strength	%	92	90	97	90
$\beta^*_{\rm maxDS}$	[m]	300	300	300	300
B1 B2 imbalance	%	30	30	30	30
Symmetry up to		Q3	Q3	Q5	Q5

values have been optimized to keep the quadrupoles of the insertion far from their higher or lower limits when a full optics is matched to the arc with the specific ATS left/right phase constraints. A rounding to 1 mm has been applied to the varying lengths.

A triplet design has been carried out assuming the four maximum gradients (g) 170 T/m, 150 T/m, 118 T/m and 100 T/m. Table 1 shows that $\beta_{\rm max}$ scales with $g^{-0.63}$, $l_{\Sigma \rm lQ} = l_{\rm Q1} + 2l_{\rm Q2} + l_{\rm Q3}$ with $g^{-0.73}$, $l_{\rm total} = l_{\Sigma \rm lQ} + d_{12} + d_{22} + d_{23}$ with $g^{-0.58}$, $\beta_{x,\rm Q4}$ with $g^{-0.77}$, $\beta_{y,\rm Q4}$ with $g^{-0.40}$. The peak beta functions consistently occur in the second half of Q2. It is more efficient to optimize the gradient of Q1 than the one of Q3 for gradients below 150 T/m. The 1 mm rounding does not spoil the optimization. The effect of 16% in the drift lengths gives a 1.5% increase of $\beta_{\rm max}$ and $l_{\rm total}$, but a 1.8-2.7% decrease of $l_{\Sigma \rm lQ}$. A subsequent scan of the matching conditions [6] has shown a limited variation of the accepatable parameters.

The values of the boundary conditions of the triplet have a strong impact on the possibility to match an LHC low-beta insertions to the periodic arc Twiss parameter, in particular, when the left and right phase advance from the IP are constrained. In fact there is a lower bound ($\beta^*_{\rm opt}$) of β^* for which optics solutions exists. The LHC insertions have generally more free parameters (22) than optics constraints (16), always allowing multiple solution, however each free parameter is bounded and additional "soft" constraints like quadrupole margins, the imbalance between the gradient of the Beam 1 and 2 apertures of the same 2-in-1 magnet or peak beta functions in the dispersion suppressor are normally included. Another soft constraint, the left/right antisimmetry up to Q5 helps to regularise the optics solutions avoiding peak beta functions in the DS and big imbalance between the Beam 1 and 2 aperture, but increases the optics limits by few centimeters. Those constraints are normally included to qualify an acceptable optics but they reduces the number of possible solutions and affect the value of the optics limit. The choices on those soft constraints have to be reported to allow fair comparisons.

In addition when β^* shrinks, $\beta_{\rm max}$ and the chromatic aberrations increase up to a point, called chromatic limit $\beta^*_{\rm chrom}$, for which the sextupoles in the arcs in phase with the triplet exceed their strengths. Table 2 shows that the optics and chromatic limit are very similar, although the first becomes slightly higher than the second for low gradients, indicating that below 120 T/m the optics matchability starts to play a role.

TRIPLET APERTURE

Once the coil aperture of the triplets is taken into account and a gradient is chosen compatible with a technology, it is possible to calculate the β^* reach (assuming no optics limitation thanks to the ATS), by choosing a geometric model of the vacuum chamber and the beam halo dimensions. The gradient is chosen to be compatible with either NbTior Nb_3Sn technology. The gradients are reported also as a fraction of an estimated short sample limit (data from [7]), but they do not reflect any particular magnet design. The vacuum chamber is modeled as an octagon rescaled from the Phase I project [4] linearly with the aperture. All options considered are equivalent in terms of aperture margins (calculated using the n_1 method for the beam halo with nominal LHC parameters [8]) to the ones of the nominal LHC at $\beta^* = 55\,\rm cm$. Table 3 and Table 4 shows the β^* reach for round and flat aspect ratios, respectively. The results show that large apertures enables smaller β^* than increasing the gradient. As an example a solution with 140 mm at 100 T/m is equivalent in terms of aperture margins to one with 120 mm at 180 T/m. Although the last one generates more compact and optically flexible layouts.

Table 3: Round β^* reach and impact on the luminosity leveling time as a function of the aperture of the triplets.

$\phi_{\rm IT}$ mm	grad T/m	β^* cm	N_1 10^{11}	N_2 10^{11}	t h
150	144(83%Nb_3Sn)	13.0	1.99	1.21	6.06
150	96(83%NbTi)	17.0	2.03	1.36	5.24
140	150(80%Nb_3Sn)	15.0	2.01	1.29	5.64
140	100(80%NbTi)	19.0	2.05	1.42	4.89
120	180(83%Nb_3Sn)	18.6	2.05	1.42	4.96
120	120(83%NbTi)	24.0	2.11	1.58	4.14
80	257(80%Nb_3Sn)	39.0	2.33	1.99	2.65

It is also possible to evaluate the impact of a reduced β^* in terms of luminosity and luminosity lever arm if the Piwinski angle is used for leveling. For round β^* the leveling is performed by the crab cavities [9], while for flat β^* one can efficiently level with the crossing angle in the plane of the large β^*. In Table 3, N_1 is the bunch intensity at the beginning of the leveling (5σ half crossing angle), N_2 at the end of the leveling (head-on) to reach $5{\cdot}10^{34}\,\rm cm^{-2}s^{-1}$ with LHC nominal beam parameters and t is the time in hour it takes to pass from N_1 to N_2. In Table 4 the leveling starts at the value indicated by α and stops at 6.5σ half crossing

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Table 4: Flat β^* reach and impact on the luminosity leveling as a function of the aperture of the triplets.

ϕ_{IT} mm	grad T/m	$\beta^*_{x,y}$ cm	α σ	N_1 10^{11}	N_2 10^{11}	t h
150	144	31.0, 6.6	6.5	1.69	n/a	n/a
150	144	32.8, 8.7	13	2.33	1.74	4.6
150	96	32.5, 8.7	6.5	1.78	n/a	n/a
150	96	34.3, 12.0	11.5	2.36	1.91	3.6
140	150	32.5, 7.5	6.5	1.73	n/a	n/a
140	150	33.0, 9.0	10	2.10	1.80	2.4
140	100	33.5, 10.0	6.5	1.83	n/a	n/a
140	100	34.3, 12.0	9.5	2.18	1.91	2.2

angle since flat optics are more sensitive to the long-range beam-beam effects (see [5]).

DYNAMIC APERTURE

In the nominal LHC the dynamic aperture (DA) for the squeezed optics is dominated by the beam-beam effects and field quality of magnets in the triplet area. When the ATS is used, the β blow-up in the arcs enhances the detrimental effect of the field imperfections of the arc dipoles and quadrupoles and of the main field of the arc sextupoles. It is therefore important to quantify the DA reduction due to the arcs in order to the keep its contribution negligible with respect the other sources.

Tracking studies have been performed including only the lattice sextupole and a field quality model of the imperfections of the main dipole and quadrupoles. Table 5 compares the minimum DA over 5 angles and 10^5 turns with a different combinations of β^* and ATS β^* shrinking factor ($f^{\mathrm{ATS}}_{x,y}$) using the SLHC 3.01 and 3.1b layout [10],[11],[12]. Case a represents a nominal like scenario with a very good baseline DA. Shrinking β^* with the ATS by a factor 2.6 and 4, Case b and d, reduces the DA linearly with β^*. This is the case also for the flat optics, Case e and g. The same squeezed β^* can be achieved by different combination of pre-squeeze β^* and ATS shrinking factors. This is the case for b, c and e, f. Case b and e offer a much better baseline because the blowup in the arcs is smaller. Option c, d and f, g have the same beta function in the arcs, however Case c, d have a better DA because the pre-squeeze is far from the chromatic limit ($\beta^* = 60$ cm with a gradient of 123 T/m) therefore the strong sextupole strength is smaller.

CONCLUSION

Triplets for the HL-LHC have been analyzed using several figure-of-merit and organized in scaling laws. The LHC low-beta insertion supports triplets with gradient larger than 100 T/m, without sensible degration of the optics flexibility. Higher gradients are favoured since they decrease chromatic aberrations and generate more compact designs. However, thanks to the ATS, higher gradients should not compromise the available aperture. Ideally the largest possible aperture should always be preferred as long as any other hardware and cost constraints not mentioned here are respected, like the field quality of the magnets, the size of the cryostasts, the cooling capabilities, the tunnel integration. Ideally the pre-squeeze β^* should be set to maximize the use of the arc sextupoles by reaching the optics or chromatic limit, whatever comes first.

Table 5: Dynamic aperture in sigma for several combination of β^* and ATS multiplication factors including only the arc field imperfections of LHC as built.

	$\beta^*_{x,y}$ cm	$f^{\mathrm{ATS}}_{x,y}$	15°	30°	45°	60°	75°
a	40,40	1,1	39.3	40.4	39.5	39.1	39.6
b	15,15	8/3,8/3	23.3	26.0	22.5	21.5	20.9
c	15,15	4,4	18.3	17.7	17.6	17.4	16.0
d	10,10	4,4	15.4	17.6	14.5	14.2	13.7
e	7.5,30	16/3,4/3	16.2	17.0	17.0	18.1	16.8
f	7.5,30	8,2	12.9	13.9	14.1	13.4	12.1
g	5,20	8,2	11.3	11.0	12.0	12.1	11.3

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