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HLLHCV1.1: OPTICS VERSION FOR THE HL-LHC UPGRADE*

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Abstract

The optics and layout of the HL-LHC are evolving as the new hardware is being studied and integrated, any additional requirements from the experiments detailed, and other constraints of different nature clarified. Here we present the changes of version 1.1 of the optics and layout with respect to the previous version 1.0, which include the current hardware choices and an outlook on the main resulting optics limitations and the possible future evolutions of the layout.

INTRODUCTION

The High-Luminosity LHC project (HL-LHC) [1] relies on a reduction of β^* at the interaction points (IP) of the ATLAS and CMS experiments, IP1 and IP5 respectively. Larger aperture magnets [2] are foreseen to be compatible with the increased beam size in the interaction region (IR) and crab cavities [3] to compensate for the geometric reduction factor introduced by the crossing angle. The achromatic telescopic squeeze scheme (ATS) [4] is foreseen to preserve optics flexibility and guarantee the correction of the chromatic aberrations when reducing β^*, at the cost of extending the optics transitions to the arcs and neighbouring insertions and of increasing the beam size in the arcs. The new scheme also requires a stronger quadrupole in IR6 and will benefit from an additional sextupole in the arcs around the IR1,5.

This paper presents the latest baseline layout and optics models of the HL-LHC, labelled HLLHCV1.1, which is an evolution of HLLHCV1.0 and previous layouts [5]. We will also give an outlook of the future evolution of the layout based on recent developments from hardware studies.

LAYOUT

The HL-LHC layout is based on the nominal LHC with changes in particular in the straight sections of IR1 and IR5. A summary of the layout changes with respect to the LHC is given in Table 1. Figure 1 shows a sketch of the layout for the right part to IR5 (the left part is symmetric with respect to the IP and the layout of IR1 is identical to the IR5 layout). The main changes from HLLHCV1.0 to the HLLHCV1.1 are:

- updated triplets and interconnection lengths,
- change of position of the Q4 magnets,
- one additional cavity module (4 instead of 3) per side, beam and per IR,
- a different hardware for Q5 (MQY at 1.9 K) in IR1 and IR5 instead of a new MQYL (longer MQY) type,
- a different hardware for Q5 in IR6 (an additional MQY, thus two MQYs, instead of a new MQYL type magnet),
- revised orbit corrector layout in the D2-Q4 area [6].

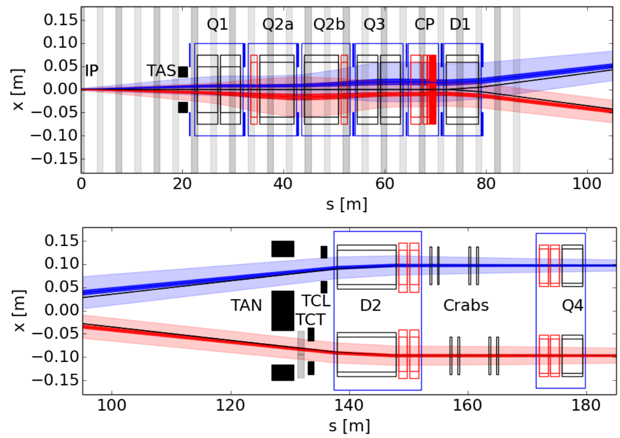

Figure 1: Sketch of the Layout on the Right Side of IP1 and IP5 from the IP to D1 (top) and from D1 to Q4 (bottom). Dark blue and red area show the 2σ beam envelops of Beam 1 and Beam 2. Light blue and red areas show the 12 σ beam envelops with imperfections (20% beta beating and 2 mm orbit error). On the top plot, gray bands highlight the location of the parasitic encounters for 25 ns bunch spacing and small blue boxes the BPMs.

The Q4 has been moved towards the arc in order to reduce the required voltage of the crab cavities and with the additional benefit of more available space for the additional crab cavity module and other equipment to be installed in the crab cavity region. Furthermore, the crab cavity modules are arranged in a different layout: two staggered pairs to optimize the required deflecting voltage regardless of the crossing plane. In HLLHCV1.0 the crossing and separation scheme bumps were closed just before the crab cavities with the orbit corrector at D2 (MCBRD), in order to minimize the orbit at the location of the crab cavities, however leading to a large strength of the MCBRD orbit correctors. In HLLHCV1.1 a considerable reduction has be achieved by sharing the strength needed for the crossing scheme bump between the orbit corrector at Q4 and the MCBRD at D2 at the cost of a non-zero residual orbit at the location of the crab cavities [6]. HL-LHC optics needs stronger Q5s in IR1/IR5/IR6 than those of LHC and for IR1/IR5 also with larger aperture. For Q5 HLLHCV1.1 adopts less expensive solutions as compared to the new magnet type (MQYL) proposed in HLLHCV1.0. In IR1/IR5 the existing MQM is replaced with the current Q4 (MQY) fitted to be cooled at 1.9 K to reach 200 T/m. Another alternative would have been to use a double MQYY as Q5 in IR1/IR5 to give more strength in Q5 (used mainly for large β optics) and more aperture that could be used in alternative optics schemes [7]. In IR6 doubling the existing MQY brings enough strength for the ATS squeeze optics.

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Table 1: New Elements Proposed for the HL-LHC Upgrade

Type	Name	IR	Changes with respect the LHC as built
TAXS	Absorber	1,5	54 mm aperture instead of 34 mm
MQXFA	Q1/3 a/b	1,5	140 T/m, 150 mm aperture instead of 70 mm, 4.000 m instead of 6.370 m
MQXFB	Q2a/b	1,5	140 T/m, 150 mm aperture instead of 70 mm, 6.800 m instead of 5.500 m
MCBXFB	Corrector	1,5	1.200 m nested H and V orbit correctors (2.5 Tm) in Q2a and Q2b
MCBXFA	Corrector	1,5	2.200 m nested H and V orbit correctors (4.5 Tm) on the non-IP side of Q3
M…XF	Corrector	1,5	a_2, b_6, a_6, b_5, a_5, b_4, a_4, b_3, a_3 individual super-ferric magnet coils
MBXF	D1	1,5	6.270 m long, 35 Tm, 150 mm aperture (cold magnet instead of 6 warm modules)
TAXN	Absorber	1,5	2-in-1, 145 mm to 154 mm aperture separation, aperture 80 mm instead of 52 mm
MBRD	D2	1,5	7.780 m, 35 Tm, 2-in-1 105 mm aperture (instead of 80 mm) moved by 15 m towards the IP
MCBRD	Corrector	1,5	2-in-1, H (or V) strong orbit corrector (4.5 Tm) on the non-IP side of D2
ACFCA	Crab Cav.	1,5	4 modules per beam, side, IP and with 3.5 MV deflecting voltage per cavity
MCBYY	Corrector	1,5	2-in-1, H (or V) strong orbit corrector (4.5 Tm) on the IP side of Q4
MQYY	Q4	1,5	2-in-1, 90 mm instead of 70 mm, 115 T/m, 3.830 m and displaced by 8.047m to the arc
MQY	Q5	1,5	MQY (70 mm) cooled to 1.9 K to reach 200 T/m instead of MQM (56 mm) at 160 T/m and
displaced by			11 m towards the arc
MS.10	sextupole	1,5	in Q10 each side of IR1, IR5 in series with the main sextupoles
MQY	Q5	6	double MQY similar to IR2, IR8 Q4 assemblies

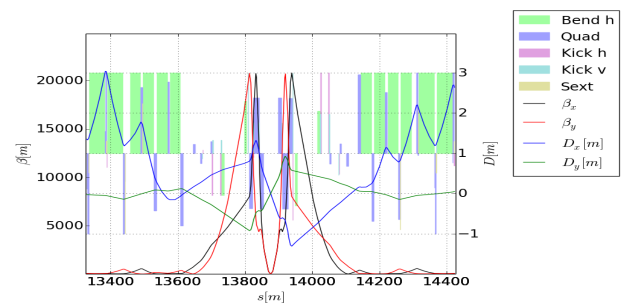
The long-range beam beam (LRBB) compensator has not been integrated yet in the layout (see for [8] for a possible implementation).

OPTICS

The optics has not changed significantly with respect to HLLHCV1.0, besides the marginal changes induced by the small layout variations and the increase of the β-function at the crab cavity location to reduce the crab cavity voltage by 5%. By moving the Q4 towards the arc and rematching the triplet strength, the margin in the Q7 strength (one of the limiting factors) could be increased and then used for the increase of the β-function at the crab cavity location in the plane where is smaller. The optics and crossing and separation scheme changes are illustrated in Fig. 2 on the basis of the squeezed collision optics with $\beta^* = 15$ cm. HLLHCV1.1 optics set has been completed with large β optics for experimental insertion for VDM scans. Table 2 shows a summary of the optics and main specifications available in the official repository [9]. It is expected that dynamic aperture will be slightly worse for the HLLHCV1.1 optics compared to the HLLHCV1.0 for the same β^* and field quality [10] due to the split of Q1 and Q3 and the intentional increase of beta function in D2 and Q4.

MECHANICAL APERTURE

The mechanical aperture model has been updated following the corresponding hardware studies. An overview of the vacuum elements is given in Table 3 together with the aperture expressed in terms of σ using the expected tolerances for the HL-LHC [11]. The aperture values have to be compared with a target of 12 σ for the elements up to Q4, which is the minimal value still assuring a protection of the element by the tertiary collimators, and 20 σ for all other elements [12]. The triplet available aperture is below



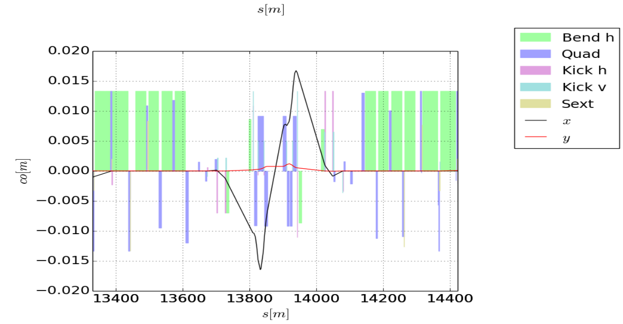


Figure 2: IR5 Beam 1 HLLHCV1.1 optics (top) and orbit (bottom) for $\beta^* = 15$ cm. The crossing bumps are shown for a pre-collision stage for which a parallel separation is applied orthogonal to the crossing angle plane. For squeezed collision optics, the β-functions scale rigidly with $1/\beta^*$ up to Q5 and the crossing angle scales accordingly to the desired beam-beam separation. The orbit bump has been matched with a small offset in D2 to optimize the mechanical aperture by using in addition orbit correctors in Q5.

the specifications and optimization work including design of the beam screen [13] and collimator settings is ongoing. The aperture of the new TAXS (called TAS in the LHC) has been reduced from 60 cm to 54 cm upon a request from the experiments based on the assumption that a smaller aperture would offer more protection in case of failures, however the

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Table 2: Optics Configurations Available in the HL-LHC Repository, with Relevant IP1 and IP5 Parameters. $\beta^*_\times$, $\beta^*_\parallel$ are the β-functions in the crossing and parallel separation plane, $\theta_\times$, $\Delta_\parallel$ are the crossing angle and the parallel separation (the external ones for IR2 and IR8), respectively.

name	$\beta^*_\times$ [m]	$\beta^*_\parallel$ [m]	$\theta_\times$ [μrad]	$\Delta_\parallel$ [mm]	$\times_{\text{plane}}$ IP1/5
injection: $\beta^*_{2,8}$ = 10 m, $\theta_{\times 2,8}$ = 340 μrad					
`inj15`	15.0	15.0	590	4	any
`inj`	6.0	6.0	590	4	any
as injection but 205 T/m IR2, 8 triplets and coll. tunes					
`endoframp`	6.0	6.0	590	4	any
ATS phase advances, β^*_8 = 3 m					
`presqueeze`	3.0	3.0	590	1.5	any
`presqueeze`	0.44	0.44	590	1.5	any
telescopic squeeze					
`round`	0.15	0.15	590	1.5	any
`sround`	0.10	0.10	720	1.5	any
`flat`	0.075	0.30	550	1.5	V/H
`sflat`	0.050	0.20	670	1.5	V/H
`flathv`	0.075	0.30	550	1.5	H/V
`sflathv`	0.050	0.20	670	1.5	H/V
ion, $\beta^*_{2,8}$ = 50 cm					
`ion`	0.44	0.44	590	1.5	any
VDM, $\beta^*_{2,8}$ = 30 m					
`vdm`	30	30	590	1.5	any

available margins can further decrease in case a transverse orbit offset at the IP is at the same time requested by the experiments. The TAXN (called TAN in the LHC) aperture has been optimized based on energy deposition studies [14] and to be compatible the aperture requirements. Additional masks and TCLs have been introduced to protect the superconducting magnets from the incoming beam, while an additional TCT has been proposed to reduce the allowed protected aperture of D2 and Q4 [12]. For D2 and Q4 assemblies a new octagonal beam screen is under study [15], which is advantageous for flat beam optics. If the orbit has to readjusted in order to compensate for alignment errors of the crab cavities, the aperture might also decrease, in particular for D2 [6].

CONCLUSIONS AND OUTLOOK

The HLHLCV1.1 layout and optics version is a step forward for the finalization of the HL-LHC scenarios. It has been used by the hardware teams to carry out integration and hardware compatibility studies. No relevant optics changes have been introduced in this version besides the adaptation to the hardware changes, an optimization of the crab cavity

Table 3: Geometry and Dimension of the Beam Screen or Beam Pipe and Beam Aperture for IR1 and IR5 for Round and Flat Collision Optics. The worst case among the magnets of the same class is taken. The beam aperture is calculated assuming the following mechanical tolerances: 20% beta-beating, 2 mm orbit error, $2 \cdot 10^{-4}$ energy spread and 10% of spurious dispersion [11]. For the octagonal shape the value represents the H,V gap and the gap at 45°. For the rectellipse shape the values correspond to the H,V gap.

Assembly	**Shape**	**Size** [mm]	**Round** [σ]	**Flat** [σ]
TAXS	Round	54.0	12.31	11.10
Q1	Octagon	98.0, 98.0	14.93	13.65
Q2-3	Octagon	118.0, 118.0	10.98	10.97
D1	Octagon	118.0, 118.0	11.60	11.88
TAXN	Round	80.0	14.71	12.04
D2	Octagon	87.0, 78.0	18.59	13.95
Crabs	Round	84.0	25.69	18.47
Q4	Octagon	73.8, 63.8	21.60	17.11
Q5	Rectellipse	48.0, 57.8	25.45	17.99
Q6	Rectellipse	35.3, 45.1	25.54	18.05

voltage and D2 orbit corrector strength. HLHLCV1.1 is expected to be superseded this year by a new iteration that would take into account the outcome of the integration studies. In fact, the triplet gradient has been recently reduced to increase margins [16], leading to longer quadrupoles to cope with a smaller gradient. The location of the equipment (vacuum valves and BPMs) in between the IP and first quadrupole (Q1) and the value of L^* is under review. Both updates will modify the triplet layout and result in a larger β^*. Studies are also on-going to optimize the BPM position with respect to the long-range beam-beam encounters.

The new triplet layout in IR1/5 will require a change of β^* and a review of the IR1/IR5 squeeze sequence and optics. BPM alignment optics (i.e. zero triplet strength) will need to be demonstrated. The apertures are expected to deteriorate at constant β^* in the area between TAXS and Q4 for the new layout. Possible locations for the LRBB compensator will be identified. An optimisation of the IR4 optics beam instrumentation or hollow electron lenses [17] might be needed. The IR6 ATS squeeze will need to be revisited since in few collimators there is a smaller beam transverse area with possible impact on the damage threshold [18]. It is foreseen to update the IR8 crossing scheme at injection to that used in 2015 [19].

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