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HIGH LUMINOSITY LHC OPTICS AND LAYOUT HLLHCV1.4*

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Abstract

The goal of the High Luminosity Project is the upgrade of the LHC to deliver an integrated luminosity of at least 250 fb^{-1} per year in each of the two high-luminosity, general-purpose detectors ATLAS and CMS. This article presents the latest layout design and the corresponding optics features, which comprise optimisation of the orbit corrector and crab cavity systems, and new estimates of the performance reach thanks to the new concept of fully remote alignment. In addition, the new optics version incorporates improvements required by beam instrumentation, dump system, and collimation system, as well as low-beta solutions for the LHCb experiment.

HL-LHC LAYOUT EVOLUTION

The HL-LHC [1,2] layout and optics have been incrementally updated since version 1.0 [3,4] following the development of the new hardware, cost optimisation exercises, new requests from the experiments, and also the experience gathered during LHC Run 2 [5–7]. This article presents the main layout and optics features of the latest official optics version called HLLHCV1.4 [8,9]. The HL-LHC project is based on the LHC [10] ring with an extensive modification of the interaction regions (IR) around the interaction points (IP) 1 and 5, which host the ATLAS and CMS experiments, respectively. The comprehensive list of the upgrades in the scope of the HL-LHC project is available in Ref. [1,2].

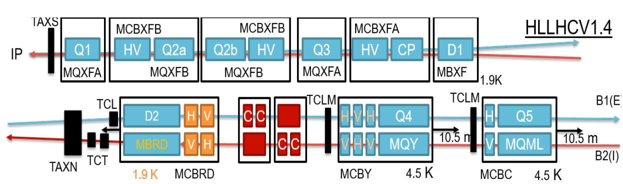

Figure 1: HLLHCV1.4 layout of the right side of IR1 and IR5 with quadrupoles (Q), non-linear corrector package (CP), dipoles (D), collimators and masks (TC), crab cavities (CC), and passive absorbers (TAX).

The layout of IR1 and IR5, shown schematically in Fig. 1 (active and passive elements with nomenclature), has been designed to reduce the beam size at the IP, introduce additional shielding inside the triplet quadrupoles [11] and D1 dipole, and to add crab cavities (CC). This has been achieved by redesigning all beamline elements from TAXS (collision debris absorber) to D2, increasing their aperture compared to the LHC. Nb_3Sn technology has been used to maximise the product of gradient and aperture of the triplet quadrupoles (Q1-3) and their length has been optimised to minimise the ratio of peak-β functions in the triplet over β^*, thus minimising chromatic aberrations and sensitivity to field imperfections [12]. The geometric reduction factor due to the low β^* value and the corresponding increase of the crossing angle is compensated by using crab cavities. The CCs are installed as close as possible to the IP to maximise their effect using the large β functions. Therefore, the D2 separation dipole, the collimators and the TAXN collision debris absorber must be installed in a location with limited transverse space, calling for new, special designs. Additional orbit correctors on the non-IP side of the D2 allows closing the crossing bump upstream of the CCs, as they can tolerate minimal orbit offset from their electrical centre. The stringent orbit correction constraints at the IP and CCs [13], the need to re-use the LHC Q4 assembly, and the reduction of dose to personnel, imposes the necessity of the addition of a fully remote alignment system [14] to the baseline design, which also allows reductions in the use of orbit correctors (see Fig. 2 for the present budget and [15] for a detailed comparison). The location of the Q4 has been optimised taking into account the cryogenic infrastructure and the additional absorber masks to limit radiation to the superconducting coils that are part of the baseline.

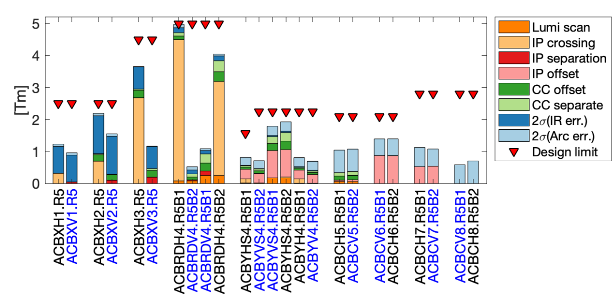

Figure 2: Orbit corrector budget in IR1 and IR5 at 7 TeV. The strength budget includes operational settings (IP crossing and separation, luminosity scan) and correction of imperfections (IP offset, offset and separation at the CCs, and compensation of local and global quadrupole misalignments). The IP offset is meant to compensate for the small step in the Q5 area due to the full remote alignment. The remaining strength can be used to further refine the orbit without using the full remote alignment (e.g. 0.5 mm of IP shift).

OPTICS CONFIGURATIONS

Different optics configurations provide the conditions for the p-p programme [16], ion program [17], and van der Meer (VDM) scan measurements at the four experimental IPs [9]. The baseline p-p scenario foresees the so-called *Round* optics with equal β^* in the transverse planes. Alternative configurations, called *FlatCC* and *Flat*, are also provided to improve performance with and without crab cavities by further squeezing β^* in the parallel separation plane.

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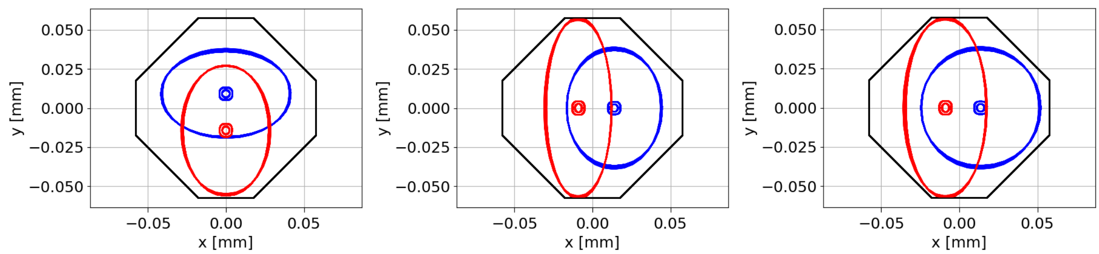

Figure 3: Beam 1 and 2 envelopes at a reference value of 12.7 σ in Q3 right of IR5 for Round (left), Flat (centre), and FlatCC (right). The protected aperture depends on the detailed optics (see Table 3). Round optics has more aperture margin than flat optics (0.4σ). In flat optics, D1 has a smaller aperture in the horizontal plane by 0.1σ to be reviewed once measured mechanical tolerances from prototypes will be available.

Figure 3 shows the beam envelopes for the above-mentioned p-p optics at the location of the aperture bottleneck in the triplets, where the limit on the minimum normalised aperture is well respected. For the ion programme, low β^* optics are designed for all experiments. The VDM configuration provides large β^* values for luminosity-calibration runs. Note that no special high-beta runs with $\beta^* > 30$ m are planned for HL-LHC. Table 1 summarises the nominal β^* values for the four experimental IRs. Luminosity levelling is assumed in all experiments by varying β^* (IP1 and IP5) or the parallel separation (IP2 and IP8).

The following sections describe the optics constraints and optics design choices of the IRs and the eight arcs.

Table 1: Main HL-LHC optics configurations. Flat optics have a larger β^* in the crossing plane to reduce the impact of the geometrical reduction factor and a smaller β^* in the orthogonal plane to increase luminosity. The β^* in flat optics depends on the effective crossing angle, which is reduced with crab cavities (FlatCC).

Optics	β^* IP1/5 [m]	β^* IP2 [m]	β^* IP8 [m]
Injection	6	10	10
Round	0.15	10	1.5
Flat	0.075/0.30	10	1.5
FlatCC	0.075/0.18	10	1.5
VDM	30	30	30
Ions	0.5	0.5	1.5

IR1, IR5: ATLAS and CMS

IR1 and IR5 optics are identical and fulfil the phase advance requirements for the Achromatic Telescopic Squeeze (ATS) scheme [18] from $\beta^* = 2$ m to 0.5 m, which allows different telescopic factors for a given final β^*. The triplet strength has been adjusted to maximise the effect of the CCs within the range of matching conditions and quadrupole strength limits. The aperture of the new beam line elements has been designed to be compatible with both Round and Flat optics, which requires larger apertures in particular from the TAXN (neutral absorber) to Q5 (see Table 2).

IR2, IR8: Alice and LHCb

Beam injection is performed in IR2 (Beam 1) and IR8 (Beam 2). Hence, the optics in these IRs fulfil the injection constraints (aperture and strength of triplets and Q4-Q5 on the right side of IR8 and left side of IR2). During the ramp, the triplet strength in IR2 is reduced to reach the nominal value at flat top. IR2 optics implements also the optics matching transitions for the telescopic squeeze of IR1. For the ion programme, β^* is also squeezed during the ramp. The triplet strength in IR8 is reduced during the ramp to reach the nominal value at flat top and simultaneously β^* is lowered to reach 3m. Optics with $\beta^* = 1.5$m are also provided, but they imply a reduction of the crossing angle to be compatible with the TCDDM (injection protection fixed mask) aperture. These optics are useful to reduce the contribution to the head-on beam-beam interaction on the tune footprint, as well as to provide the necessary virtual luminosity for the possible LHCb Phase-II upgrade [19]. Flat optics can be also considered to optimise aperture restrictions versus luminosity. The telescopic transition for the squeeze of IP1 can be applied when β^* in IP8 is in the range 1.5 m $\leq \beta^* \leq$ 3 m [20].

Table 2: IR1 and 5 apertures in beam σ for Round, FlatCC, and Flat optics. Margins and tolerances are taken on beam size, orbit, and mechanical imperfections [21].

	Round	FlatCC	Flat
TAXS	16.3	14.0	14.0
Q1	17.7	15.9	15.9
Q2-3	13.1	12.7	12.7
D1	13.5	12.6	12.6
TAXN	18.0	14.1	14.1
TCT-TCL	18.8	14.4	14.4
D2	19.3	14.5	14.5
Crab cavities	21.8	15.4	15.4
Q4	19.3	13.6	13.6
Q5	21.1	14.9	14.9
Q6	26.7	18.9	18.9

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IR6: Dump System

IR6 hosts the dump system and the optics is constrained by the necessary internal phase advance, minimum β functions at the protection devices, and the global phase advance from the dump kickers (MKDs) to the tertiary collimators (TCT) [22]. The insertion is not equipped with the same number of individually-powered quadrupoles as the experimental IRs, which makes it harder to fulfil all constraints [23], including the telescopic transition for IR5 and therefore some compromises need to be made. For instance, the TCDQ jaw (a single-jaw movable absorber protecting the downstream elements from asynchronous beam dumps) needs to be positioned more than 3 mm for 2.1×10^{11} ppb away from the circulating beam, which implies an additional constraint on the horizontal β-function at the TCDQ to ensure that the normalised aperture is in-between secondaries and tertiary collimators.

Table 3 summarises the MKD-TCT phase advance for the various optics solutions. The obtained aperture margins are sufficient for all configurations. Note that a horizontal crossing angle in IP5 would generate a reduced aperture margin ($1.2\,\sigma$), which is still acceptable. This, together with the preference for a vertical crossing plane for the CMS forward physics programme [24], led to the decision of selecting a vertical crossing plane in IP5 as baseline. A flat optics to be used with CCs and vertical crossing plane in IP5 is under development, but the optics constraints are more severe, resulting in a larger minimum β^* in IP1/5. All these optics requires pushing the Q5 strengths beyond their nominal values in the last part of the squeeze. Recent tests without beam [25] proved the required strength for 7 TeV operations could be achieved without lowering the current operational temperatures (4.5 K).

Table 3: Aperture margins for the three optics considered. The MKD-TCT phase advance determines the protected aperture in the horizontal plane [21], whereas in the vertical plane the protected aperture is limited by the cleaning efficiency. The choice of the crossing plane maximises the global aperture margins, placing the largest horizontal envelopes in IR1 due to the more favourable MKD-TCT phase advances.

	Round	FlatCC	Flat
MKD-TCT [°] IP1/5	18/31	23/23	7/25
Protected H IR1 [σ]	11.2	11.4	11.2
Protected H IR5 [σ]	11.9	11.4	11.7
Protected V IR1/5 [σ]	11.2	11.2	11.2
β^* Xing/Sep [cm]	15/15	18/7.5	30/7.5
Xing angle [μrad]	500	480	490
Ap. Xing plane [σ]	13.1	14.2	15.6
Ap. Sep plane [σ]	16.5	12.7	12.7
Xing plane IP1/5	H/V	V/H	V/H
Ap. Margin IR1/5 [σ]	1.9	1.3	1.5

IR4: RF and Instrumentation

IR4 optics fulfils the constraints for RF cavities (i.e. low dispersion), pick-ups, kickers, and beam profile measurement devices (i.e. large β functions). Moreover, suitable optical conditions for the e-lens [26], which is not yet in the baseline, are also feasible. The telescopic transition for IP5 uses, as much as possible, the right side of the IR4, while keeping the Twiss parameters in the dogleg region, hosting the RF cavities and most of the beam instrumentation devices, constant during the squeeze at IP5. The total phase advance of IR4 is also adjusted to optimise the MKD-TCT phase advance.

IR3, IR7: Collimation System

IR3 and IR7 optics do not change during the operational cycle besides what is needed to match the boundary conditions, when the neighbouring arcs change phase advance due to the ATS scheme. In order to provide additional spare magnets, two warm quadrupoles will be removed from the Q5 and a new optics has been designed, at a small cost of optical flexibility and a small loss of aperture at injection.

Arcs

The ATS scheme [18] defines the optics change of the four arcs around IR1/5 during the operational cycle. The other four arcs are used to match the nominal working point (e.g. $Q_x = 62.31$,$Q_y = 60.32$ in collision) and to optimise the MKD-TCT phase advance during the telescopic transitions. The sextupole families implement the chromatic correction needed by the ATS scheme. Orbit bumps are also provided to compensate the dispersion mismatch introduced by the crossing scheme in IR1/5. The combination of β-beating waves from the ATS scheme and orbit bumps reduces the aperture margin in the arcs and possibly limits the amplitude of the telescopic squeezing.

SUMMARY AND OUTLOOK

HLLHCV1.4 layout and optics configurations implement optimal optical conditions at the experimental IPs, while being compatible with the machine constraints. Future studies will focus on the detailed optics transitions for all schemes and to analyse possible variants of the operational scenarios, e.g. combined ramp and squeeze with ATS, or crossing plane gymnastics for LHCb. Furthermore, the installation of an additional sextupole, part of the HL-LHC baseline since the beginning, is being scrutinised to assess whether this modification can be avoided by a clever optics design.

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