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HLLHCV1.0: HL-LHC LAYOUT AND OPTICS MODELS FOR 150 MM NB3SN TRIPLETS AND LOCAL CRAB-CAVITIES

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The paper presents the latest layout and optics models for the HL-LHC upgrade project. As an evolution from the previous version SLHCV3.1b, it integrates the new Nb3Sn triplet (140 T/m, 150 mm) with all the additional magnets needed to be compatible with a β* reach of 15 cm and beyond. The collision optics implements the ATS [1] scheme which is able to provide very low value of β* and at the same time warrants outstanding control of the chromatic aberrations within the strength limits of the existing arc sextupole scheme of the LHC. The optics models include the injection and collision optics for proton and ion operations foreseen for the HL-LHC, with improved squeezeability of the existing IR2 and IR8 insertions. An aperture model and a series of optics matched in thin lenses complete the needs for a large range of dedicated beam dynamic studies (dynamic aperture, beam-beam effects, collimation).

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Abstract

The paper presents the latest layout and optics models for the HL-LHC upgrade project. As an evolution from the previous version SLHCV3.1b, it integrates the new Nb_3Sn triplet (140 T/m, 150 mm) with all the additional magnets needed to be compatible with a β^* reach of 15 cm and beyond. The collision optics implements the ATS [1] scheme which is able to provide very low value of β^* and at the same time warrants outstanding control of the chromatic aberrations within the strength limits of the existing arc sextupole scheme of the LHC. The optics models include the injection and collision optics for proton and ion operations foreseen for the HL-LHC, with improved squeezeability of the existing IR2 and IR8 insertions. An aperture model and a series of optics matched in thin lenses complete the needs for a large range of dedicated beam dynamic studies (dynamic aperture, beam-beam effects, collimation).

INTRODUCTION

The High-Luminosity LHC project (HL-LHC [2]) relies on a strong reduction of β^* at the interaction points (IP) of the ATLAS and CMS experiments, IP1 and IP5 respectively. New magnets of larger aperture are foreseen to be compatible with the increase of the beam size in the interaction region (IR). A novel optics and squeezing mechanism (ATS) is also foreseen to preserve the optics flexibility and guaranty the correct-ability of the chromatic aberrations when reducing β^*, at the cost of some operational complications and small dynamic aperture degradations.

We present the latest layout and optics models for the HL-LHC baseline, labelled HLLHCV1.0, which is an evolution of SLHCV3.1b [3]. The layout is based on triplet using Nb_3Sn technology, and integrates crab cavities for preserving the luminosity gain with $1/\beta^*$ [4].

LAYOUT

The new layout integrates the latest hardware proposals [5] that required an update of the optics:

- Q1, Q3 split into two 4 m long low-β quadrupoles;
- distance of 0.5 m and 2.0 m in between magnetic extremities of consecutive magnets whether or not they are in the same or different cryostats, respectively;
- use of superferric non-linear non-nested corrector magnets ([6, 7]), which have lower field but smaller heads, and better radiation resistance compared to SC nested alternatives;
- reduction of the integrated strength of D1 and D2 to what is strictly needed by Nb_3Sn triplets compared to longer NbTi quadrupoles with the same aperture.

The crab cavities are kept in between D2 and Q4 with 3 modules per beam and IR side to both obtain enough voltage to support the crossing angle needed at low β^*, and decrease the impact of failure scenarios [8].

An new MQYL quadrupole type is proposed to replace Q5 in IR1, IR5 and IR6, in order to respond to the new needs of aperture and strength. Alternative scenarios with two existing MQY in IR6 operating at 200 T/m (1.9 K) are being discussed but not implemented in the present version.

An additional sextupole is still needed at Q10 in IR1 and IR5 (replacing an MCBC module with a standard MSCB module of approximately the same length which contains an orbit corrector and a sextupole), because no pre-squeeze optics with low gradient triplet has yet been found fulfilling phase advances for which an even number of sextupoles are sampled by the ATS beta wave peaks. A summary of the layout schematics and specifications is shown in Figure 1 and Table 1.

OPTICS

HLLHCV1.0 contains the main optics features already present in SLHCV3.1b, with new optics for IR2 and IR8 to respond to physics requests for ALICE and LHCb for which the phase advances have been re-optimized to be compatible with injection, $\beta^* = 50$ cm in IP2 and IP8 in non-ATS mode and ATS collision optics. The repository contains several optics configuration that can be grouped in:

- injection: one baseline with lower than nominal β^* for IR1 and IR5 and few options at higher values;
- end of ramp: optics for which IR2 and IR8 have triplet strengths compatible with 7 TeV operations;
- pre-squeeze: optics with special IR1 and IR5 phase advances that allow the arc sextupoles to locally cancel the off-momentum beta-beating induced by the triplet, a pre-requisite to implement the telescopic part of the ATS squeeze. Two versions are provided at the lowest and largest possible β^* in IR1 and 5. In this

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Table 1: New beam line elements proposed for the HL-LHC upgrade for IR1 and IR5 where not specified.

Name	**Type**	**Changes with respect the LHC as built**
TAS	Absorber	60 mm aperture instead of 34 mm
Q1a/b, Q3a/b	Quadrupole	140 T/m, 150 mm aperture (instead of 70 mm), 4.002 m instead of 6.37 m.
Q2a, Q2b	Quadrupole	140 T/m, 150 mm aperture (instead of 70 mm), 6.792 m instead of 5.50 m hosted in separated cryostats
MCBXD	Corrector	1.2 m nested H and V orbit correctors (2.5 T.m) on the IP-side of Q2a and non-IP side of Q2b
MCBXC	Corrector	longer nested H and V orbit correctors (4.5 T.m) on the non-IP side of Q3
MC...X	Corrector	non-nested $a_2, b_6, a_6, b_5, a_5, b_4, a_4, b_3, a_3$ superferric magnet coils
D1	Dipole	6.69 m long, 35 Tm, 160 mm aperture (cold magnet instead of 6 warm modules)
TAN	Absorber	2-in-1, 145 mm aperture separation, elliptical aperture (82, 74) mm instead of (52, 52) mm
D2	Dipole	10m, 35 Tm, 2-in-1 105 mm aperture (instead of 80 mm) moved by 15 m towards the IP
MCBRD	Corrector	2-in-1, H (or V) strong orbit corrector (7 Tm) on the non-IP side of D2
ACRAB	RF deflector	3 modules offering a 12.5 MV deflecting voltage per beam and IP side
Q4	Quadrupole	2-in-1, 90mm aperture (instead of 70 mm), 160 T/m $\times$ 3.2 m
Q5	Quadrupole	2-in-1, 70mm aperture (instead of 56 mm), 160 T/m $\times$ 4.8 m moved by 11 m towards the arc
MS	sextupole	in Q10 in series with the main sextupoles
Q5 in IR6	Quadrupole	2-in-1, 70mm aperture (instead of 56 mm), 160 T/m $\times$ 4.8 m (longer version of the existing MQY type)

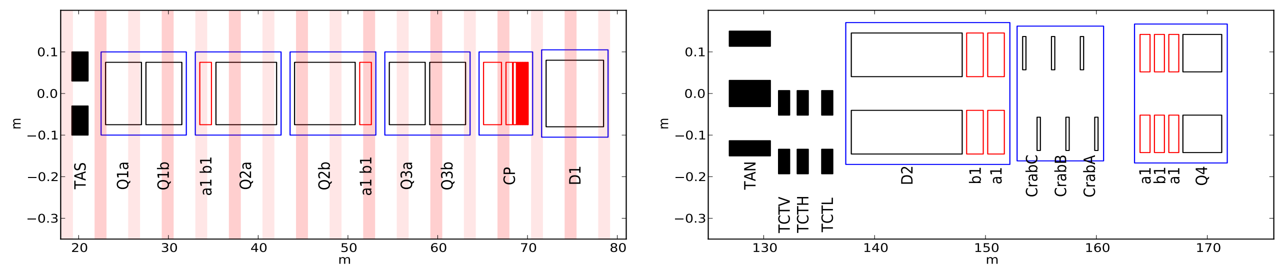

Figure 1: Sketch of the layout on the right side of IP1 and IP5, from the triplet to Q4. The red bands highlight the location of the parasitic encounters for 25 ns bunch spacing.

and the following optics family, IR8 has β^*=3 m to support physics in LHCb.

- squeeze: optics for very low β^* in IR1 and IR5 obtained with the ATS scheme: there are two versions of round β^* (nominal and ultimate) with tunable orientation of the crossing plane (default H/V for IR1 and IR5) and four versions of flat optics with nominal and ultimate β^* and different choice of crossing plane (H/V and V/H for IR1 and IR5, respectively).
- ions: operations at nominal $\beta^* \sim 50$ cm for all experimental insertions without using the ATS.

A summary of the optics and main specifications are listed on Table 2.

A pre-squeeze optics has been found with both the triplet at the maximum strengths and equal peak beta for the maximum efficiency in terms of aperture. Several models of beam screen are implemented in particular octagon shapes with and without ISO tolerances resulting in 112 mm and 121 mm in the midplane (see Fig. 2).

The requirements on the MCBX strengths has been specified from the crossing angle reach and the strengths needed for the correction of transverse misalignments. A Montecarlo simulation assuming a maximum IT misalignment of

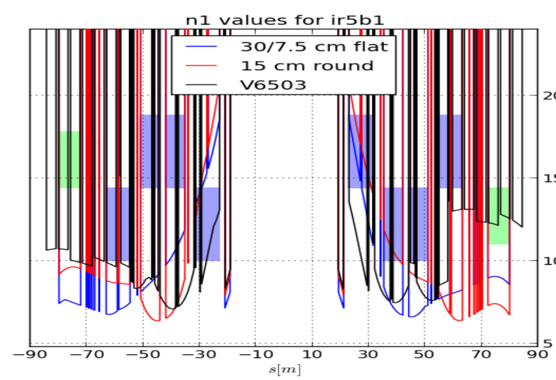

Figure 2: Aperture plot for IR5 beam 1 with horizontal crossing angle and octagonal beam screen with ISO tolerances.

$\pm$0.5 mm shows that, by using an 8-corrector scheme, one needs 1.2 Tm for MCBX1/3, 2 Tm for MCBX2 and 0.1 Tm for the MCBRD, and the peak residual orbit is 0.5 mm. Alternatively, a 10-corrector scheme reduces the strength requirements to 0.8 Tm for MCBX1,2,3 but increases the MCBRD strength up to 0.4 Tm and the peak residual orbit can reach 1.4 mm. MCBX1,3 and MCBRD are used to generate the crossing angle and require 0.4 Tm, 2.1 Tm, 4.5 Tm

Table 2: Optics configuration 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]	$\times_{\rm plane}$ IP1/5
injection: $\beta^*_{2,8} = 10$ m, $\theta_{\times 2,8} = 340\mu$rad					
`inj_17`	17.0	17.0	340	4	any
`inj_11`	11.0	11.0	340	4	any
`inj`	6.0	6.0	490	4	any
as injection but 205T/m IR2,8 triplets and coll. tunes					
`endoframp`	6.0	6.0	490	4	any
ATS phase advances, $\beta^*_8 = 3$ m					
`presqueeze`	3.4	3.4	620	1.5	any
`presqueeze`	0.44	0.44	360	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	360	1.5	any

for 590 μrad, respectively. The strengths of the MCBX1 are extremely sensitive to the triplet setting, as shown by a Montecarlo simulation on random triplet strength variations of ± 5 T/m. However a large fraction of configurations is still compatible with with present specifications.

The crab cavities can be installed either by alternating the modules between Beam 1 and Beam 2, as shown in Fig. 1, or by arranging them consecutively. In the first case the maximum required voltage is independent on the crossing plane (12.35 MV for 590 μrad), while in the second case it ranges from 11.9 MV to 12.6 MV depending on the crossing plane. The second option is attractive at the cost of having a different layout for IR1 and IR5. Efforts to reduce the required voltage and, at the same time, gain optics flexibility are still being carried out at the cost of extending the scope of the IR upgrade [9].

Few families of optics transitions from injection to presqueeze have been found for a less recent version of the layout and shows a continuous path with few change of slopes (for details see [10]). A further reevaluation is needed and it will be included in the repository.

The IR2 and IR8 phase advances have been optimized against two conflicting configurations: injection optics favoring larger phases and low β^* optics for ion operation favoring smaller phases (see a study on [11]). The new phase advances for IR2 and IR8 are (2.95, 2.67) and (3.02, 2.8), respectively, compared to (3.02,2.9) for both IRs. The arc phase advances have been adjusted accordingly in order to preserve the tune working point and, as a consequence, all the other remaining IRs have been rematched, while preserving the features already present in SLHCV3.1b.

REPOSITORY

The layout and optics are available as madx files hosted on AFS [12]. They rely on the latest LHC optics and layout V6.503 with additional information for the new elements in particular the aperture models and non-linear error tables. For single particle tracking with Sixtrack thin optics version of each optics will be provided using the novel slicing mechanism introduced in madx [13] together with error assignments, correction algorithms and beam-beam kick installation routines adapted from SLHCV3.1b.

CONCLUSION

Additional IR optics optimizations and hardware proposals triggered an incremental update of the HL-LHC layout and optics called HL-LHCV1.0. The repository is being finalized and benchmarked, and it will be frozen in May 2013. The layout and optics can be then used for an extended amount of time for further analysis and simulations.

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