HL-LHC PARAMETER AND LAY-OUT BASELINE

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Abstract

In this contribution the authors will present the baseline parameters of the HL-LHC project. The lay-out necessary to reach the project objectives will be described. The document will list other modifications that shall be carried out on the present LHC machine in order to reach the ambitious goal of 300 fb^{-1} delivered luminosity to the ATLAS and CMS experiments per year up to 2035. The main focus will be the foreseen modifications to be carried out during LS3, while more details concerning the relevant changes planned during LS2 are dealt with in the session "Long Shutdown 2 Strategy and Preparation" publication at this workshop.

HL-LHC BASELINE PARAMETERS

The performance of the HL-LHC machine is boxed in between the request for high integrated luminosity (ca. 3000fb^{-1} by the end of the HL-LHC exploitation over ca. 10 years of operation and translating to an annual integrated luminosity of ca. 250fb^{-1} assuming scheduled 160 days for proton physics production per year and that the HL-LHC exploitation starts with an integrated luminosity of ca. 300fb^{-1} at the end of the LHC Run III in 2022) and a maximum number of 140 events per bunch crossing. While the request for maximum integrated luminosity asks for the largest possible peak luminosity, the request for limited number of events per bunch crossing limits the peak luminosity to a maximum value of ca. $5 \bullet 10^{34}$ cm^{-2} s^{-1}. Operating the HL-LHC with the maximum number of bunches and utilizing luminosity levelling provides the best compromise for satisfying both requests. Table 1 shows the resulting baseline parameters approved by the HL-LHC Parameter and Layout Committee [1] for the standard 25ns bunch spacing configuration together with the parameters for the nominal LHC configuration and two alternative scenarios. These alternative scenarios are interesting in case LHC operation during Run II reveals problems either related to the emittance preservation along the LHC cycle for high intensity operation (the so called BCMS filling scheme allows the preparation of small emittance beams at the price of a reduced number of bunches) or enhanced electron-cloud effects at 25ns operation. The fall back solution for the latter scenario is a 50 ns bunch separation scheme at which electron cloud effects are expected to be less of an issue, but where the peak luminosity needs to be levelled at a lower value in order to keep the number of events per bunch crossing below 140. The luminosity levelling time is of the order of 8 hours and an efficient operation of the HL-LHC machine hence requires an average physics fill length that is larger than the levelling time (e.g. ca. 10 hours). The required HL-LHC average fill length is approximately 30% larger than the average fill length of the LHC achieved during Run I (ca. 6 hours).

The baseline parameters are based on a β^* value of 15cm at the IP and the operation with Crab Cavities for compensating the geometric luminosity loss factor that becomes significant when operating with such small β^* values and a large crossing angle. These parameters coupled together imply larger aperture insertion magnets (triplet magnets, D1 and D2 and Q4 magnets) and the exploitation of a novel optics matching scheme ATS [2] that utilizes the neighbouring arcs for matching the insertion optics to the rest of the machine. The larger aperture triplet magnets of the HL-LHC insertion increases the peak fields at the coils for constant magnet gradients and implies for the HL-LHC the use of novel Nb_3Sn magnet technology and a reduction of the triplet magnet gradients with respect to the nominal LHC configuration. The use of lower quadrupole gradients implies in turn longer triplet magnets (the functional quantity is given by the integrated magnet gradients) and an increase in length of the common beam pipe region next to the IP. The use of superconducting recombination dipole magnets in IR1 and IR5 allows to a large extend a compensation of the length increase of the common vacuum beam pipe region and it limits the increase in unwanted parasitic collision points of the two beams to an acceptable level. The schematic machine lay-out from the TAXS till the start of the continuous cryostat is published and kept up to date in the drawing LHCLSXH_0010 [3]

HL-LHC: THE UPGRADE INTERVENTIONS FROM A GEOGRAPHICAL DISTRIBUTION POINT OF VIEW

HL-LHC will require modifying the machine and infrastructure installations of the LHC in several points along the ring. In particular:

- Point 4
- Point 7
- Point 2
- Point 6
- Point 1
- Point 5

The locations are listed according to the chronological order presently foreseen for the installation of the HL-LHC systems.

Point 4

Point 4 will be equipped with a new cryogenic plant dedicated to the RF systems (and other cryogenic equipment that might be installed in IR4). The installation will require a warm compressor system on surface and a junction from the surface to the underground installation where a new cold box will be placed. The cold box will then feed a dedicated RF cryogenic distribution line.

Table 1: High Luminosity LHC parameters (LHC nominal ones for comparison)

Parameter	**Nominal LHC (design report)**	**HL-LHC 25ns (standard)**	**HL-LHC 25ns (BCMS)**	**HL-LHC 50ns**
Beam energy in collision [TeV]	7	7	7	7
N_b	1.15E+11	2.2E+11	2.2E+11	3.5E+11
n_b	2808	2748	2604	1404
Number of collisions in IP1 and IP5	2808	2736 [1]	2592	1404
N_{tot}	3.2E+14	6.0E+14	5.7E+14	4.9E+14
beam current [A]	0.58	1.09	1.03	0.89
x-ing angle [μrad]	285	590	590	590
beam separation [σ]	9.4	12.5	12.5	11.4
β^* [m]	0.55	0.15	0.15	0.15
ε_n [μm]	3.75	2.50	2.50	3
ε_L [eVs]	2.50	2.50	2.50	2.50
r.m.s. energy spread	1.13E-04	1.13E-04	1.13E-04	1.13E-04
r.m.s. bunch length [m]	7.55E-02	7.55E-02	7.55E-02	7.55E-02
IBS horizontal [h]	80 -> 106	18.5	18.5	17.2
IBS longitudinal [h]	61 -> 60	20.4	20.4	16.1
Piwinski parameter	0.65	3.14	3.14	2.87
Geometric loss factor R0 without crab-cavity	0.836	0.305	0.305	0.331
Geometric loss factor R1 with crab-cavity	(0.981)	0.829	0.829	0.838
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03	3.3E-03	4.7E-03
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02	1.1E-02	1.4E-02
Peak Luminosity without crab-cavity [$cm^{-2}\ s^{-1}$]	1.00E+34	7.18E+34	6.80E+34	8.44E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2}\ s^{-1}$]	(1.18E+34)	19.54E+34	18.52E+34	21.38E+34
Events / crossing without levelling and without crab-cavity	27	198	198	454
Levelled Luminosity [$cm^{-2}\ s^{-1}$]	-	5.00E+34 [5]	5.00E+34	2.50E+34
Events / crossing (with leveling and crab-cavities for HL-LHC)	27	138	146	135
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.25	1.31	1.20
Leveling time [h] (assuming no emittance growth)	-	8.3	7.6	18.0
Number of collisions in IP2/IP8	2808	2452/2524 [7]	2288/2396	0[4]/1404
N_b at SPS extraction [2]	1.20E+11	2.30E+11	2.30E+11	3.68E+11
n_b / injection	288	288	288	144
N_{tot} / injection	3.46E+13	6.62E+13	6.62E+13	5.30E+13
ε_n at SPS extraction [μm] [3]	3.40	2.00	< 2.00 [6]	2.30

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[1] Assuming one less batch from the PS for machine protection (pilot injection, TL steering with 12 nominal bunches) and non-colliding bunches for experiments (background studies…). Note that due to RF beam loading the abort gap length must not exceed the 3μs design value.

[2] An intensity loss of 5% distributed along the cycle is assumed from SPS extraction to collisions in the LHC.

[3] A transverse emittance blow-up of 10 to 15% on the average H/V emittance in addition to the 15% to 20% expected from intra-beam scattering (IBS) is assumed (to reach the 2.5 μm/3.0 μm of emittance in collision for 25ns/50ns operation)

[4] As of 2012 ALICE collided main bunches against low intensity. satellite bunches (few per-mill of main bunch) produced during the generation of the 50ns beam in the injectors rather than two main bunches, hence the number of collisions is given as zero.

[5] For the design of the HL-LHC systems (collimators, triplet magnets,..), a design margin of 50% on the stated peak luminosity was agreed upon.

[6] For the BCMS scheme emittances well below 2.0 μm have already been achieved at LHC injection.

[7] The lower number of collisions in IR2/8 wrt to the general purpose detectors is a result of the agreed filling scheme, aiming as much as possible at a democratic sharing of collisions between the experiments.

Point 7

The Horizontal Superconducting Links

In Point 7 two horizontal SC links will be installed in order to electrically feed the 600 A circuits connected to the 2 DFBAs (DFBAM and DFBAN).

The related power converters will be installed in the TZ76 and will be connected to the superconducting links via short warm cables. The two superconducting links will then run for about 220 meters in the TZ76 and then enter into the LHC machine tunnel via the UJ76. They will then be routed for about 250 m in the LHC tunnel in order to be connected to the DFBAM and DFBAN.

New collimators in the Dispersion Suppressor

In order to protect the superconducting magnets (excess heat deposition) from off-momentum proton leakage from the main collimator system itself, some special collimators must be installed in the Dispersion Suppression region, i.e. in the continuous cryostat. The evaluation of the real need of this modification will be completed on the base of the first results of the LHC Run II.

In order to cope with the proton losses in the Dispersion Suppressor area it has been decided to install two collimators on each side of the IP in the slots presently occupied by the Main Bending Magnets MB.B8L7 plus the MB.B10L7 and the symmetric MB.B8R7 plus the MB.B10R7. Each removed dipole will be replaced by a unit composed of two 11 T dipoles separated by a cryogenic by-pass. The collimator will be positioned in the beam lines on the top of the cryogenic by pass.

Point 2

In order to limit the heat deposition from collision debris in the superconducting magnets during the ion run, collimators in the dispersion suppressor will also be installed in Point 2. In this case the installation will take place only in one slot on each side of the IP replacing the MB.A10L2 and MB.A10R2 main bends.

Point 6

In Point 6 the two quadrupole magnets Q5 will be modified in order to fulfil the needs of the new HL-LHC ATS optics. The two options presently under evaluation lead either to the exchange of the present Q5 with a new and higher gradient Q5, but featuring a type of magnet already built and in use for the present LHC, or to the design and construction of a new quadrupole with larger aperture.

Point 1 and Point 5

The largest part of the new equipment, required by the HL-LHC performance objectives, will be installed in Point 1 and Point 5. The items to be installed and actions to be carried out are listed below and are applicable to both points if not otherwise specified. The list is organized by geographical areas.

LHC machine tunnel

- De-installation: all the machine equipment from the interface with the experimental cavern, starting with the TAS, up to the DFBA (included) need to be removed. The present QRL will be also removed in the same tunnel section and a new return module will be installed to allow separating the flows of the coolant coming from the LHC QRL and the one from the new HL-LHC QRL.
- Installation of the new equipment will most likely take place in the following sequence:
    - TAXS
    - Services
    - QRL with related valve and service modules
    - Horizontal superconducting links from the DFM to the magnets
    - Magnets and crab cavity support system
    - Magnets and crab cavity
    - Distribution feed boxes for the Q1 to D1 magnet system (DFX) and for the D2 to Q6 magnet system (DFM)

The sequence of installation of the vertical superconducting links to be connected to the DFX and DFM still needs to be assessed according to the options retained for its routing.

Existing LHC tunnel service areas

The RRs on both sides of Point 1 and Point 5 will need to be re-organized and in particular it will be necessary to: de-install the power converters and other related systems linked to the powering of the removed LHC matching section and then to re-organize the remaining equipment in order to increase, if necessary, the radiation shielding.

New HL-LHC tunnel service areas

The installation of the new cryogenic plant in Point 1 and Point 5 will have two main objectives:

- Provide independent and redundant cooling capacity to feed the final focusing and matching sections left and right of each of the two High Luminosity insertions of the LHC.
- Provide redundancy to the cryogenic plant installed to cool the experimental systems.

The cold box shall be installed in underground areas (Figure 5). Presently the required volume does not exist. Therefore conceptual studies have started in order to identify the best options for building new underground caverns to install this equipment and the related service and control system. Two possible approaches are under more detailed study: the baseline corresponds to solutions with magnet power converters on the surface, and a second one with power converters in the underground areas.

New connection from the LHC tunnel and HL-LHC service areas to the surface

The following connections between the surface and the underground installation shall be made available:

- LHC tunnel, crab cavity area, to the surface. The crab cavities need to be connected to the dedicated RF power system and their control system. The present baseline is to install these services in dedicated surface buildings.
- New HL-LHC service area to the surface. These connections are necessary to link the surface part of the cryogenic plant with the cold box installed in the new underground HL-LHC service areas.
- Vertical routing of the superconducting links. In each point at least four superconducting links (2xDFBX, 2xDFBL) will need to be routed from the surface to the underground areas.

New surface installation

The following installations shall find space on surface in Point 1 and Point 5 and in their proximities:

- Crab cavity RF power and services hosted in two ad hoc surface buildings. They shall be positioned on the surface, vertically directly above the tunnel position where the crab cavities will be installed. There will be two surface buildings for each point, one on the left part of the machine and one on the right part. The surface extremities of the ducts/shaft for the crab cavity coax or shaft shall be housed inside this building.
- Cryogenic installation. On surface the warm compressors and the other part of the cryogenic plant shall be installed.
- Power converters, upper extremities of the superconducting links, protection systems and energy extraction system related to the circuits fed via the superconducting link. This area shall be possibly located near the surface part of the cryogenic plant and in any case on the top of the surface extremity of the routing of the vertical superconducting link.

CONCLUSIONS

The HL-LHC project has produced a reference table for the baseline parameters and a sound lay-out baseline that will allow meeting the set targets. In this contribution both the parameter table and general lay-out modifications including main machine infrastructure have been discussed. It is worth recalling that, in addition to the baseline here described, the project has also developed a list of technical options with the objective to provide a robust risk mitigation plan and keep the path open towards further performance improvements.

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REFERENCES

[1] HL-LHC Layout and Parameter Committee, https://espace.cern.ch/HiLumi/PLC/default.aspx

[2] S. Fartoukh. Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade, CERN-ACC-2013-0289, 2013 Published in: Phys. Rev. Spec. Top. Accel. Beams 16 (2013) 111002APS.

[3] CERN CDD Drawing number LHCLSXH_0010.