Chapter 1

High-luminosity Large Hadron Collider

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1 High-luminosity Large Hadron Collider HL-LHC

1.1 Introduction

The Large Hadron Collider (LHC) was successfully commissioned in 2010 for proton–proton collisions with a 7 TeV centre-of-mass (c.o.m.) energy. It delivered 8 TeV c.o.m. proton collisions from April 2012 until the end of Run 1 in 2013. Following the Long Shutdown 1 (LS1) in 2013–2014, it operated with 13 TeV c.o.m. proton collisions during Run 2 from 2015 until the end of 2018, reaching a peak luminosity twice the nominal design value. At present (2020), the LHC is in Long Shutdown 2 (LS2) during which further consolidation measures (insulation and retrofitting of the protection diode connections) are being pursued; these should enable the LHC to reach its nominal design beam energy of 7 TeV. As a consequence of the coronavirus pandemic, LS2 will last almost one year longer than foreseen, with Run 3 now planned to start at the beginning of 2022.

The truly impressive performance of the LHC has reconfirmed CERN as a European and global centre for high-energy physics, and as an important incubator of knowledge and technology development. After the discovery of the long-awaited Higgs boson in 2012 by the LHC experiments ATLAS [1] and CMS [2], the LHC continues to act as catalyst for a global effort unrivalled by any other branch of science: out of the 12 thousand CERN users, more than 9 thousand are scientists and engineers using the LHC, half of which are from countries outside the EU [3].

The LHC will remain the highest energy accelerator in the world for at least the next two decades. Its full exploitation was the highest priority of the European Strategy for Particle Physics Update (ESPPU) of 2013 [4]. The high priority has been confirmed by the recent 2020 ESPPU [5]. The above referenced strategy deliberations, as well as those of the Snowmass process of 2013–2015 [6], recognized that to extend its discovery potential, the LHC will need a major upgrade in the 2020s, firstly to extend its operability by another decade or more, and secondly to increase its collision rate and thus the delivered integrated luminosity. The upgrade design goal is a fivefold increase of the instantaneous collision rate and a tenfold increase of the integrated luminosity with respect to the LHC nominal design values. The necessary developments required a dedicated research effort lasting more than 10 years; studies included prototype developments and the manufacture of ground-breaking equipment. The machine configuration of the upgrade, the high-luminosity LHC (HL-LHC), relies on new operation modes (e.g. levelled luminosity operation with dynamic optics adjustments) and a number of innovative, profoundly challenging, technologies. These include: cutting-edge 11 to 12 T superconducting magnets; novel magnet designs (e.g. canted cosine theta and super-ferric magnet designs), very compact superconducting RF cavities for beam rotation with ultra-precise phase control; new technologies and materials for beam collimation; and high-current superconducting links with almost zero energy dissipation.

HL-LHC federates the efforts and R&D of a large international community towards its ambitious objectives and contributes to establishing CERN as a focal point of global research cooperation and leadership in frontier knowledge and technologies. HL-LHC relies on strong participation from international partners who make important in-kind contributions. These partners include Non-Member States laboratories in the USA, Japan, China, Canada and Russia as well as leading institutions and universities from the Member States: INFN (Genova and Milano-LASA, IT); CIEMAT (Madrid, ES); STFC (UK) and other British universities and institutions; Uppsala University (FREIA Laboratory, SE); and several other partner institutes (see Table 1-2). These participations with in-kind contributions, as well as the participation of other institutes who provide skilled personnel, are key ingredients for the execution of the construction phase. The US LHC Accelerator R&D Program (LARPhas been essential for the development of some of the key technologies for the HL-LHC, such as the large-aperture niobium–tin (Nb_3Sn) quadrupoles and the crab cavities. The governance, initially modelled for a design study phase, was tailored in 2016 to support the construction phase.

1.2 Project overview

The present LHC baseline programme, as defined at the end of 2019 (the consequences of the coronavirus pandemic are included in the present version, with shift of beginning of Run 3, as much as it is known today) is shown schematically in Figure 1-1. During Run 1 the LHC was operated with 50 ns bunch spacing. After the consolidation of the electrical splices between the superconducting magnets (and many other consolidation measures) in LS1, the LHC was operated in Run 2 at 13 TeV centre-of-mass energy. The bunch spacing was reduced to 25 ns, the design value, and the luminosity was progressively increased, attaining the nominal design luminosity of 1×10^{34} cm^{-2} s^{-1} on 26 June 2016. A peak luminosity of 2×10^{34} cm^{-2} s^{-1} was achieved in 2018 thanks to the small emittances of the beam delivered by the injectors and to a smaller than design β^* value of 30 cm (cf. 55 cm nominal value). This luminosity is nearly the ultimate value of the original LHC design report, but it has been obtained with around the nominal bunch population (ca. 1.2×10^{11} p/bunch) rather than the ultimate value of 1.7×10^{11} p/b. This high-luminosity and the excellent availability of the machine and injectors have yielded a record annual integrated luminosity of 65 fb^{-1} in 2018. In the Run 3 period from 2022 to 2024 the LHC aims to further increase the integrated luminosity total: the present goal is to reach 350 fb^{-1} by the end of Run 3, well above the initial LHC goal of about 300 fb^{-1}. In 2018 it was experimentally confirmed that the peak luminosity is limited at the value of around 2×10^{34} cm^{-2} s^{-1} by the heat deposition from luminosity debris and the lack of sufficient cooling of the inner triplet magnets.

Figure 1-1: LHC baseline plan for the next decade and beyond showing the collision energy (upper line) and luminosity (lower line). LS2 sees LHC consolidation and the HL-LHC underground excavation, as well as the upgrade the LHC injectors and Phase 1 upgrade of the LHC detectors. After LS3, the machine will be in the high-luminosity configuration. Covid-19 restrictions have led to the shift of the start of Run 3 to February 2022 while the start of LS3 is maintained at end of 2024.

To fully exploit the physics potential of the LHC, CERN established the high-luminosity LHC project at the end of 2010 [7] with the following targets:

- A peak luminosity of 5×10^{34} cm^{-2} s^{-1} with levelling operation;
- An integrated luminosity of 250 fb^{-1} per year, with the goal of 3000 fb^{-1} in the 12 years or so after the upgrade.

This integrated luminosity is about ten times the predicted luminosity reach of the LHC in its initial configuration.

The main equipment upgrades and layout modifications for HL-LHC will be carried out in the 600 m long insertion regions of LHC Point 1 (P1 - ATLAS) and LHC Point 5 (P5 - CMS). Other parts of the LHC need to be modified as well to deal with the upgraded performance yielding a total length of more than 1.2 km of modified machine and with one further 1 km of additional technical services and equipment required by the new components.

The high-luminosity LHC (HL-LHC) project started as a design study with a contribution by the European Union and various partners in the EU, USA and Japan, federated under the *EC-FP7-HiLumi LHC Design Study* (since then *HiLumi* is frequently used as a project nickname). After the approval of the new European Strategy for Particle Physics by CERN Council on 30 May 2013 [4], the HL-LHC project became CERN's major construction project for the next decade. A series of steps have been taken since then to get a complete approval of the HL-LHC:

- Delivery of a complete preliminary design report (PDR) [8] under the EC-FP7-HiLumi LHC Design Study and first full evaluation of the project cost in 2013.
- Insertion of a budget line (covering most of the cost) in the CERN Medium Term Plan (MTP) [9], with indication for the total cost, in June 2014.
- Implementation of a Cost & Schedule Review (international panel of experts, composed by the CERN Machine Advisory Committee complemented by additional experts). The first meeting in March 9-11, 2015 scrutinized the full project as described in Ref. [8]. The report is available upon request (some information is confidential).
- Modification of the layout for civil engineering (with power supplies of magnets and RF in the underground area with a 'double decker' arrangement – new service galleries located above the existing LHC tunnel), more suitable to the actual needs and conditions in 2015.
- Insertion of the whole budget for the years 2016–2020 (the 5 years covered by MTP approved in 2015), with indication of the total CtC (Cost-to-Completion) of the project until full installation into CERN's MTP, in June 2015.

Thanks to the above-mentioned initiatives, the project and its budget for construction were approved as part of the MTP by the Council at its 16 September 2015 Session. The MTP document also reported, for information, the total cost of the project and the yearly budget profile until 2026.

In spring 2016 the CERN management submitted to Council the proposal for a global approval of the HL-LHC, describing the goals of the upgrade, the physics case for the HL-LHC, and the technology challenges. The proposal, described in Ref. [10], covers all the project period including installation and commissioning, and gives a total material cost for the HL-LHC of 950 MCHF. It is to be noted that this figure covers the high-luminosity LHC, i.e. the materials for collider with its infrastructure, while it does not include the cost of detector upgrades. The document was approved in the 181st session of the CERN Council on 16-17 June 2016. It is remarkable that HL-LHC has become the first project approved directly by the CERN Council since the final approval of the LHC in 1996.

Since then, all equipment has been designed with an engineering margin with respect to the instantaneous heat deposition and the integrated radiation dose. The concept of an ultimate performance is used for an additional performance increase. By using these margins, it should be possible to push the machine peak levelled luminosity 7.5×10^{34} cm^{-2} s^{-1} increasing the average pile-up, i.e. the number of events per bunch crossing, in the detectors up to around 200. This luminosity level should enable to collect 300 to 400 fb^{-1}/year, provided the experiments can digest this pile-up level and the reduction of engineering margins does not impact too severely on the machine reliability. In terms of total integrated luminosity, the ultimate performance could yield about 4000 fb^{-1}.

Similarly, all magnetic circuits have been designed with a 8–10% margin with respect to the powering at nominal beam energy of 7 TeV [11]. By using these margins, one might hope to operate the LHC eventually at a beam energy of 7.5 TeV [12] and the HL-LHC aims at providing sufficient engineering margins for the new elements to be compatible with this ‘ultimate’ beam energy, or, when these margins cannot easily be integrated within the HL-LHC resource envelope, to identify the required additional upgrades.

The high-luminosity LHC project is also working in close collaboration with the CERN project for the LHC Injector complex Upgrade (LIU) [13], the companion ATLAS and CMS upgrade projects of 2019–2021 and 2025–2027 and the upgrades planned for both LHCb and ALICE in 2019–2021.

1.2.1 Luminosity

The (instantaneous) luminosity, defined as the number of potential collisions per unit area per second, can be expressed for the LHC as:

$$L = \gamma \frac{n_\mathrm{b} N^2 f_\mathrm{rev}}{4\pi\, \beta^*\, \varepsilon_\mathrm{n}} R; \quad R = 1/\sqrt{1 + \frac{\theta_\mathrm{c}\, \sigma_z}{2\sigma}} \tag{1-1}$$

where γ is the relativistic gamma factor; n_b is the number of bunches per beam colliding at the Interaction Point (IP); N is the bunch population; f_rev is the revolution frequency; β^* is the value of the beta function at the collision point; ε_n is the transverse normalized emittance; R is a luminosity geometrical reduction factor from the crossing angle not including the Hourglass effect; θ_c is the full crossing angle between colliding beam; and σ, σ_z are the transverse and longitudinal r.m.s. sizes, respectively.

With the nominal parameter values shown in Table 2-1, a luminosity of 1×10^{34} cm^{-2} s^{-1} is obtained, with an average pile-up per bunch crossing) of $\mu = 27$ (note $\mu = 19$ was the original forecast at LHC approval due to uncertainties in the total proton cross-section at higher energies).

The discovery reach of the LHC ultimately depends on the integrated luminosity defined as: $L_I \equiv \int_{\Delta t} L\, dt$, or, more directly, the total number of events recorded. Integrated luminosity depends on instantaneous performance (the luminosity) and on the availability of the machine, i.e. the operating time in collision mode, Δt in the above equation. Improving availability (a challenge when machine parameters are pushed near to their maximum acceptable values) is as important as increasing the instantaneous luminosity.

1.2.2 Present luminosity limitations and hardware constraints

Before discussing the new configuration of the HL-LHC, it is useful to recall the LHC systems that will need to be changed, and possibly improved, because they either become vulnerable to breakdown and accelerated aging, or because they may become a bottleneck for operation at higher performance levels and in a higher radiation environment. This goes well beyond the ongoing regular LHC consolidation.

- **Low-β inner triplet quadrupoles** (see Chapter 3). After about 300 fb^{-1} some components of the inner triplet quadrupoles and their corrector magnets will have received a dose of 30 MGy, entering into the region of possible radiation damage. The quadrupoles may withstand a maximum of 400 fb^{-1} to 700 fb^{-1}. But some corrector magnets of nested type might already fail above 300 fb^{-1}, though solid figures are not available. The replacement of the triplet magnets and the associated correctors must be envisaged before damage occurs. Furthermore, the current triplet aperture limits the potential β^* reach and thus the attainable peak luminosity. As mentioned above, the cooling power of the triplet is also limited to a value corresponding to a peak luminosity of about 2×10^{34} cm^{-2} s^{-1}.

- **Cryogenics** (see Chapter 9). To increase intervention flexibility and in order to provide the required additional cooling power, the cooling of the inner triplets and part of the matching section magnets needs to be upgraded with a dedicated 1.9 K refrigerator. Separating the triplet cooling from the rest of the arc magnets avoids the need to warm-up an entire arc in the case of interventions in the straight sections near the triplet magnets.
- **Collimation** (see Chapter 5). The collimation system has been designed for the operation of the LHC with its nominal parameters. The upgrade of this system considers, among other things, the need for a lower impedance of the jaws, required for the planned increase in beam intensities and a new configuration to protect the new inner triplet magnets.
- **The dispersion suppressor (DS) regions** (see Chapter 11 and Chapter 5) have been identified as a possible LHC performance limitation, because of a leakage of off-momentum particles from the IPs into the first and second main superconducting dipoles. For P1 and P5 a solution has been found through the implementation of orbit bumps and steering the losses away from the active magnets and into the connection cryostat. For P2 a solution has been found by modifying the optics and placing collimators in a special warm by-pass in a suitably modified connection cryostat. For P7, where the leakage is due to the interaction of primary beam with the collimation system, the solution is more elaborate: an LHC main dipole will be substituted by dipoles of equal bending strength (~120 T·m) obtained by a higher field (11 T) and shorter length (11 m) than those of the LHC dipoles (8.3 T and 14.2 m). The space gained is sufficient for the installation of a warm by-pass hosting additional collimators.
- **Superconducting (SC) links** (see Chapter 6A) for the remote powering of cold circuits. A solution is being pursued for the removal of power converters from the LHC tunnel: for the HL-LHC this equipment will be installed in a new underground gallery following a global optimization study that favours the use of a novel technology that exploits MgB_2 superconductors.

Other systems will potentially become problematic with the aging of the machine and the increased radiation level that comes with higher levels of beam current, luminosity, and integrated luminosity, for example, a number of absorbers and the beam dumps. Their replacement in the frame of the HL-LHC project gives the opportunity of improving their performance or to adapt to new requirements from the experiments.

1.2.3 Luminosity levelling and availability

Both the consideration of energy deposition by collision debris in the interaction region magnets, and the necessity to limit the peak pile-up in the experimental detector, impose an a priori limitation on the acceptable peak luminosity. The consequence is that HL-LHC operation will have to rely on luminosity levelling Figure 1-2 left), the luminosity profile without levelling quickly decreases from the initial peak value due to ‘luminosity burn-off’ (protons consumed in the collisions). With luminosity levelling the collider is designed to operate with a constant luminosity at a value below the virtual maximum luminosity. The integrated luminosity achieved is almost the same as that without levelling, (Figure 1-2 right), in an ideal running configuration without premature fill aborts. The advantage, however, is that the maximum luminosity and peak energy deposition are lower. Among the various methods of levelling, the present favoured one is dynamic variation of β^* during the run. However, variation of crab cavity voltage and/or variation of beam separation are also considered.

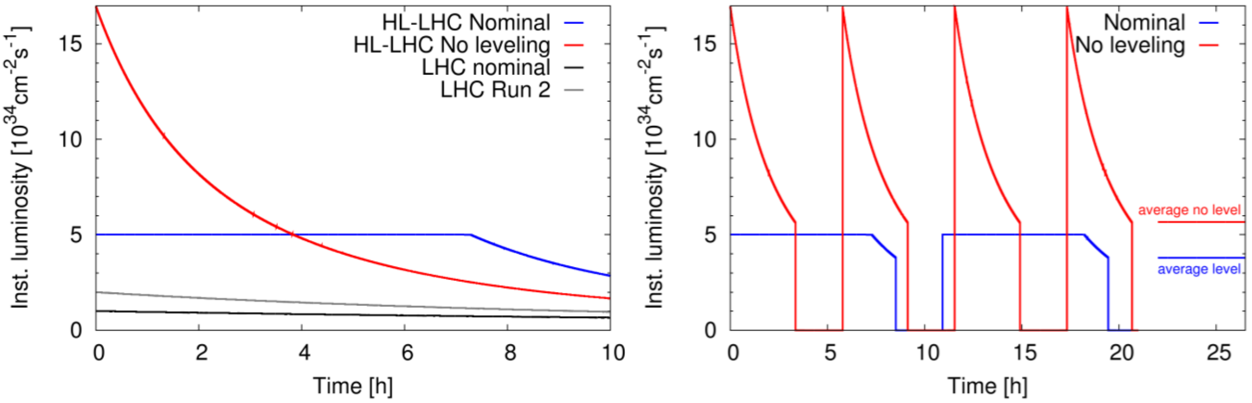

Figure 1-2: (left) Luminosity profile for a single long fill for LHC nominal design and LHC Run 2 operation, as well for HL-LHC with and without levelling. (right) Luminosity profile with optimized run time, without and with levelling, and average luminosity indicated in both cases (solid lines).

A hypothetical 'actual' luminosity cycle for the HL-LHC is depicted in Figure 1-3. With this cycle and assuming 160 days of physics operation per year, the HL-LHC needs a physics efficiency of about 50% in order to reach the 250 fb^{-1} of the nominal design performance, in line with what has been achieved during the last years of the LHC operation, but with twice the beam current. The high-luminosity LHC must therefore also be a high availability machine.

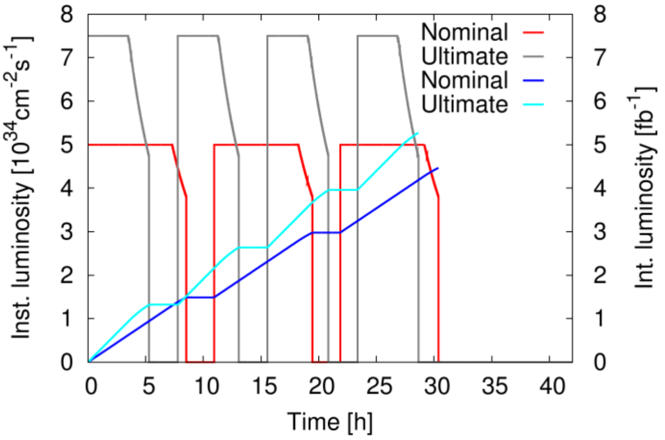

Figure 1-3: Luminosity cycle for HL-LHC with levelling and a short decay (optimized for integrated luminosity) both for nominal levelling (5×10^{34} cm^{-2} s^{-1}) in red and for ultimate levelling (7.5×10^{34} cm^{-2} s^{-1}) in grey. Integrated luminosity is also plotted for both design and ultimate luminosity operation (dark blue and light blue lines respectively).

1.2.4 HL-LHC parameters and main systems for the upgrade

Table 1-1 lists the main parameters foreseen for the HL-LHC operation (a complete list of parameters can be found in Chapter 2). The bunch intensity increases for HL-LHC from 1.15×10^{11} ppb to 2.2×10^{11} ppb, the beam emittance is improved from 3.75 to 2.50 μm and the luminosity reduction factor becomes ca. 0.34 without and 0.72 with crab cavities respectively (compared to ca. 0.84 for the LHC during Run 2). The 25 ns bunch spacing is the baseline operation however, another scheme where each eight bunches with beams are followed by four “empty bunches”, so-called 8b4e the performance with 25 ns bunch spacing. This 8b4e scheme replaces the previous alternative of 50 ns bunch spacing that is disadvantageous from the point of view of pile-up. A slightly different parameter set at 25 ns (batch compression merging and splitting scheme (BCMS)) with very small transverse beam emittance might be interesting for HL-LHC operation in case operation with high beam intensities results in unforeseen emittance blow-up.

Table 1-1: High-luminosity LHC main parameters for proton collisions.

Parameter	**Nominal LHC (design report)**	**HL-LHC 25 ns (standard)**	**HL-LHC 25 ns (BCMS)**	**HL-LHC 8b+4e**[4]
Number of bunches	2808	2760	2744	1972
Beam current (A)	0.58	1.1	1.1	0.78
Minimum β^* (m)	0.55	0.15	0.15	0.15
Peak luminosity with crab cavities $L_{\text{peak}} \times R_1/R_0$ (10^{34} cm^{-2} s^{-1})	(1.18)	17	16.9	12.1
Levelled luminosity for $\mu = 140$ (10^{34} cm^{-2} s^{-1})	-	5.0	5.0	3.8
Events/crossing μ (with levelling and crab cavities)	27	131	132	140
Maximum line density of pile-up events during fill (events/mm)	0.21	1.28	1.29	1.37

The provisional set of parameters of ion beams for the high-luminosity regime of ion collision has also been established, see Chapter 2. The parameters should be able to satisfy the ion integrated luminosity requirements of the ALICE experiment [14]. However, it must be underlined that the beam parameters are being discussed with the LIU project to assess feasibility and optimization. In addition, a discussion with the management of the LHC experiments, arbitrated by CERN management, should also provide clarification on the best sharing of ions collisions between the various experiments. It is worth reminding that the ions luminosity upgrade is available starting from Run 3 in 2021, after the completion of the LIU project.

The HL-LHC upgrade should provide the potential for good performance over a wide range of parameters. The machine and experiments will find the best practical set of parameters in actual operation. The following items are the key variables targeted for optimizing the luminosity performance by the upgrade:

- **Beam current**: the total beam current may be a hard limit in the LHC since many systems are affected by this parameter: RF power system and RF cavities; collimation system and absorbers; cryogenics; vacuum; beam diagnostics; QPS; etc. Radiation effects aside, all existing systems have been designed, in principle, for $I_{\text{beam}} = 0.86$ A, the so-called 'ultimate' LHC beam current. However, the ability to go to the ultimate limit is still to be demonstrated in operation and the HL-LHC will need to go 30% beyond ultimate beam current with 25 ns bunch spacing.
- **Beam Brightness**: The beam brightness, the ratio of the bunch intensity to its transverse emittance, is a beam characteristic that must be maximized at the beginning of beam generation and then preserved throughout the entire injector chain and throughout the operation cycle in the LHC itself. The LIU project has as its primary objective increasing the number of protons per bunch by a factor of two above the nominal design value while keeping emittance at the present low value.
- **β* reduction - stronger chromatic aberrations and aperture needs**. A classical route for a luminosity upgrade with head-on collisions is to reduce β^* by means of stronger and larger aperture low-β triplet quadrupoles. This reduces the transverse size of the luminous region resulting in a gain in peak luminosity, i.e. the luminosity at the beginning of the fill. The β^* reduction comes with an associated increase in beam sizes in the triplet magnets. For operation with a crossing angle, a reduction in β^* values also implies an increase in the crossing angle when respecting the requirement for a constant normalized beam separation over the common part of the insertion. The increased crossing angle requires in turn a further increase in the triplet magnet aperture, a larger aperture of the first separation dipole (D1), and further modifications to the matching section. Stronger chromatic aberrations coming from the larger β-functions inside the triplet magnets may furthermore exceed the strength of the existing correction circuits. The peak β-function is also limited by the possibility to match the optics to the regular beta functions of the arcs. A previous study has shown that the practical limit for β^* in the nominal LHC is around 30 cm cf. the nominal 55 cm (the LHC operated in 2018 with $\beta^* = 30$ cm at 6.5 TeV beam energy). However the Achromatic Telescopic Squeeze scheme uses the adjacent arcs as enhanced matching sections. The increase of the beta-functions in these arcs can boost, at constant strength, the

efficiency of the arc correction circuits. In this way a β^* value of 15 cm can be envisaged, and flat optics with a β^* as low as 10 cm in the plane perpendicular to the crossing plane could be realized. For such a β^* reduction the triplet quadrupoles need to double their aperture and require a peak field 50% above those in the present LHC. This implies the use of new, advanced, superconducting technology based on Nb_3Sn. Also, the separation-recombination dipole pair (D1-D2) must have a larger aperture than those in the present LHC, in order to accommodate the larger β and crossing angle coming from the lower β^*.

- **Luminosity reduction factor R**. The drawback of very small β^* is that it requires a larger crossing angle θ_c. This causes a severe reduction of the geometrical luminosity reduction factor R. Figure 1-4 shows the reduction factor as a function of β^*, assuming a constant normalized beam separation.

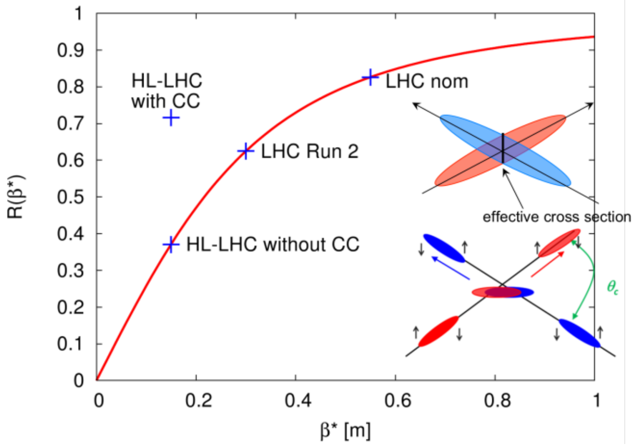

Figure 1-4: Variation of the geometrical luminosity reduction factor with β^* for a constant normalized beam separation with the indication of operational points: nominal LHC, actual LHC Run 2 and HL-LHC with and without crab cavities (CC). The top inset illustrates the bunch crossing overlap reduction effect while the bottom inset shows schematically the effect of CC on beam overlap at collision.

Various methods can be employed to at least partially mitigate this effect. The most efficient and elegant solution for compensating the geometric reduction factor is the use of special superconducting RF crab cavities, capable of generating transverse electric fields that rotate each bunch longitudinally by $\theta_c/2$, such that they effectively collide head on, overlapping perfectly at the collision points, as illustrated in Figure 1-4, see top-right inset. Crab cavities allow access to the full performance reach of the small β^* values offered by the ATS scheme and the larger triplet quadrupole magnets, almost restoring the reduction factor R to values during the nominal LHC operation despite the much larger θ_c. While the crab cavities boost the virtual peak luminosity, β^* variation during the fill – the so-called dynamic β^* squeeze – could be used as levelling mechanism. This would allow optimization of the size of the luminous region and thus the pile-up density throughout the whole fill length. With the chosen baseline of two CC per side and per beam, we achieve R values for the HL-LHC with $\beta^* = 15$ cm that are higher than those in LHC Run 2, operating at $\beta^* = 30$ cm.

1.2.5 Baseline hardware summary

The HL-LHC project encompasses the installation of new equipment and the previous de-installation, and removal of the LHC equipment over a length of about 1.2 km. The project, from the first baseline described in the PDR [8] underwent a series of changes and hardware optimization that are described in the two previous TDR versions [16][17]. Here we report only a short, not complete, functional list of the new equipment:

- Almost complete renewal of the insertion region IR1 (around ATLAS experiment) and IR5 (around CMS), from the present TAS to the Q4 quadrupole, passing through the cornerstone of the upgrade, the change of the low-β inner triplet (IT) quadrupoles. The cryogenics, cold powering and warm powering with magnet protection and vacuum systems are completely renewed, too.

- Installation of one new large 1.9 K refrigerator unit at both P1 and P5. The new refrigerators, provide the cooling power needed to absorb the five times larger heat load and, with the adoption of a new cryogenic distribution line QXL, separated from the standard arc QRL, will allow the cooling down or to the warming up of the IR1 and IR5 independently from the arcs.
- Installation of new collimators in IR1 and IR5 as well as the upgrade of most secondary collimators and a few primary ones for impedance reduction.
- Insertion of crab cavities in the Matching sections of IR1 and IR5.
- The addition of collimators in the cold dispersion suppressors regions, DS2 and DS7, in DS7 via the insertion of the 11 T dipole to create the necessary space.
- A modification of the interface to the CMS and ATLAS experiments (VAX region) and addition of a new absorber, the TANB, in IR8 for coping with LHCb increase luminosity.
- Modification of the extraction and injection systems, in particular installation of new upgraded absorbers to cope with injection failures (TDIS)
- Installation of new equipment for Beam Instrumentation (such as, but not only, Beam position monitors (BPM) with high directivity strip lines for the insertion regions, Beam Gas Vertex (BGV) profile monitors and new diagnostics for halo profile measurements), Beam vacuum (like new type of W-shielded beam screen and amorphous carbon coating of the new vacuum components).
- Major civil engineering works both underground and surface in P1 and P5, to host the technical infrastructure, the refrigerators as well as the powering and protection equipment for magnets and cavities. The underground caverns and galleries, about 1 km long in total, will be accessible also during operation with beam, thus increasing the machine availability. On surface a total of ten new buildings will be constructed.
- Three new equipment systems have been recently moved from the status 'options' to the HL-LHC baseline, following a careful preparation and endorsement by dedicated reviews and the recent 4th Cost & Schedule review [18]. They are:
    - Hollow Electron Lenses (HEL) for generating an enhanced particle diffusion in the beam halo and thus their depletion. Extrapolating the beam halo density from the LHC operation during Run 2 to the higher beam intensities of the HL-LHC implies a stored beam energy of more than 35 MJ in the beam halo for particles outside the 3-sigma beam core. This poses a significant risk for the LHC equipment in case of failures and drops in the beam lifetimes. The HEL strongly mitigates this risk and is described in Chapter 5 (as part of the Collimation system).
    - Upgrades of the LHC Beam Dump Kicker system and the main beam dump absorbers. New failure modes observed during the Run 2 operation have highlighted the vulnerability of the machine and potential hardware damage with the existing beam dump system (BDS). Upgrades of power system of the dilution kickers and new windows of the beam dump block were already implemented during LS2. However, the installation of two additional horizontal dilution kickers and a replacement of the entire beam dump absorbers by a new, more robust alternative, solves the problem, as described in Chapter 14, as part of the new BDS for the HL-LHC.
    - Crystal collimators have the potential to significantly boost the cleaning efficiency during ion beam operation. The system has been studied in the LHC with prototype hardware during LHC Run 2. An installation of a minimal configuration (4 crystals, 2 per beam) has been adopted as part of the collimation system in P7 and is described in Chapter 5.

A minor, but useful system that has been recently inserted in the baseline are the inclinometers for measuring vibrations in the machine area near the main experiments.

Now that the project has entered in construction mode there is no room for further options, at least in the present timeframe. However, a few studies are supported for the long-range beam-beam compensator system. Such a system could allow operation with smaller crossing angle and thus increase the available aperture inside the triplet magnets and extend the β^* reach and support the crossing angle compensation via the crab cavity system.

Other options that are considered highly desirable are:

- an upgrade of the power converters for the main dipole and quadrupole circuits of the LHC arcs neighbouring IP1 and IP5, where the ATS optics implies an increase in the average optic functions along the arcs. Such intervention would reduce the tune and optics perturbation due to power converter ripples and noise.
- an additional undulator in IR4 for the generation of synchrotron light for beam diagnostics purposes. The synchrotron light generated in IR4 is being used for the diagnostics of the beam abort gap population, transverse beam profile measurements and beam halo population measurements. The existing light source does not allow a parallel measurement of all the above points throughout the whole LHC cycle. In case such parallel measurements become necessary one could increase the number of available synchrotron light sources through the installation of a second undulator system in IR4.

For the equipment described above, the possible implementation is eventually left to a second stage of HL-LHC consolidation (an exception may be the power converters upgrade, given the moderate cost and the easy implementation).

1.3 Performance

The performance of the upgraded machine has evolved in time as can be seen by the three general scientific reports to the IPAC conference series [7][19][20]. The most updated projected luminosity performance along the whole life of LHC/HL-LHC machine is shown in Figure 1-5 where some “luminosity learning” due to operational experience and staging of some components is included.

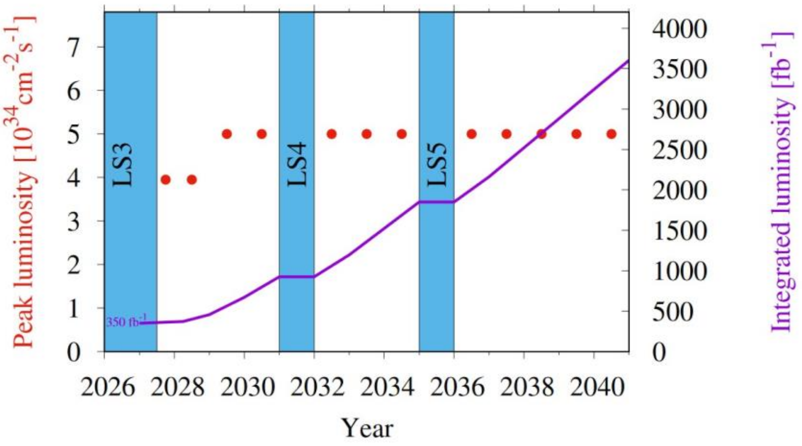

Figure 1-5: Forecast for peak luminosity (red dots) and integrated luminosity (violet line) in the HL-LHC era with nominal HL-LHC parameters.

If the performance of the HL-LHC can go beyond the design levelled luminosity value of $L_{\text{peak}} = 5 \times 10^{34}$ cm^{-2} s^{-1}, and if the upgraded detectors will accept a higher pile-up, up to 200 on average, then the performance could eventually reach 7.5×10^{34} cm^{-2} s^{-1} with levelling. With such parameters, a performance about 350 fb^{-1}/year is possible if the days of proton physics per year can be increased after LS4 and LS5. Here one foresees the end of the ALICE ion program after LS4 and a reduced need for machine development time after LS5. This would allow up to 4000 fb^{-1} to be obtained before 2040, as shown in Figure 1-6.

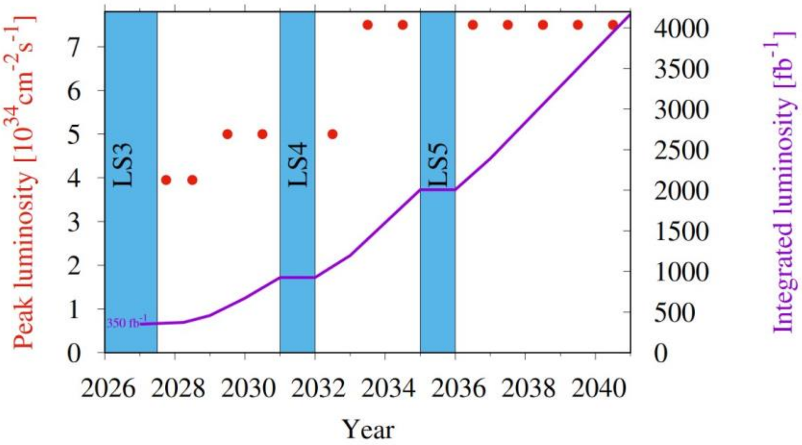

Figure 1-6: Forecast for peak luminosity (red dots) and integrated luminosity (violet line) in the HL-LHC era with ultimate HL-LHC parameters.

The graphs are based on an efficiency in luminosity production of 50%. A more detailed discussion on performance can be found in Chapter 2.

1.4 Planning and cost

1.4.1 Main milestones

The HL-LHC schedule aims at the installation of the main HL-LHC hardware during LS3, together with the final upgrade of the experimental detectors (the so-called Phase II upgrade). However, a few items have been installed or are being installed already during LS2. These include: two new DS collimators integrated in a modified version of the connection cryostat in P2 for ions; a number (40% of the total) of the new low-impedance collimators; the new TANB for P8 as well as modification of the Collider-Experiment interface for P1 and P2 and the injection protection absorbers of new design (TDIS). The 11 T dipole magnets for the new DS collimators in P7 for both ion and proton beams, could also be installed during LS2 o later during an extended technical stop during Run 3.

The HL-LHC time plan comprising past milestones, is summarized below:

- 2010: High-luminosity LHC project established at CERN as Design Study;
- 2011: Approval and start of the FP7 HiLumi LHC Design Study;
- 2014: Preliminary Design Report (PDR) published;
- 2015: First Cost & Schedule Review (C&SR-1); end of FP7-HiLumi, publication of Technical Design Report (TDR_v0);
- 2016: Validation of hardware (components and models); TDR_v0.1 and C&SR-2;
- 2018–2020: Testing of full prototypes and release of final TDR;
- 2019–2024: Construction and test of hardware components;
- 2018–2020: Main underground excavation works;
- 2019–2021: LS2 – Installation of TANB, TDIS, first batch of low impedance collimators; DS collimators in new connection cryostat in P2 and, the DS collimators with 11 T in P7 (this last point maybe completed in an extended technical stop during Run 3 or during LS3). Advancing some installation of collider-experiment interface and prototype installations for Beam instrumentation and Vacuum Work Packages;
- 2021–2023: delivery of all surface buildings;

- 2022–2024: Installation and operation test of the inner triplet string;
- 2025–2027: LS3 –Installation (new magnets, crab cavities, cryo-plants, collimators, SC Links, ancillary equipment, absorbers) and hardware commissioning. This operation is preceded by de-installation of the P1 and P5 insertion regions, as well as by excavation of the cores connecting the new HL underground areas with the LHC tunnel.

1.4.2 Cost

The Cost-to-Completion construction project, as scrutinized and endorsed by the C&SR1 in March 2015, and reconfirmed by the C&SR2 and C&SR3, amounted to about 950 MCHF for materials (including the cost for associate personnel, but excluding some items that are accounted for by the Consolidation project). In the most recent C&SR-4, held at CERN on 11-13 November 2019, an extra cost of 19 MCHF over the previous baseline was presented (the extra-cost is the balance of many cost increase and cost reduction decisions). The project also presented the proposal of adding three new main equipments to the HL-LHC baseline: Hollow Electron Lenses, a new LHC beam dumping system and minimal configuration crystal collimators, as described in the previous section. The material cost associated to this scope increase is 20 MCHF. Both the extra-cost of the previous baseline and the scope increase were endorsed by the C&SR-4 panel, by the CERN management and then inserted into the MTP2020. The total material cost of the HL-LHC construction project as of March 2020 is then 989 MCHF, to which one has to add about 100 MCHF of budget in the HL-LHC Consolidation (budget line for equipment spares and other items related to LHC and HL-LHC operation). The 989 MCHF of HL-LHC construction budget is complemented by almost 2000 FTE-y of CERN staff personnel (the cost of the more than 1300 FTE-y of CERN associated personnel are included in the material budget). At the time of the C&SR-4 about 300 MCHF of HL construction budget were already spent and about 500 MCHF engaged. This CtC is comprehensive of the baseline activities, including a contribution of 10 MCHF to cryogenic testing infrastructure and all civil engineering underground and surface buildings work (both for IP1 and IP5).

The most up-to-date budget profile from the CERN MTP is shown in Figure 1-7.

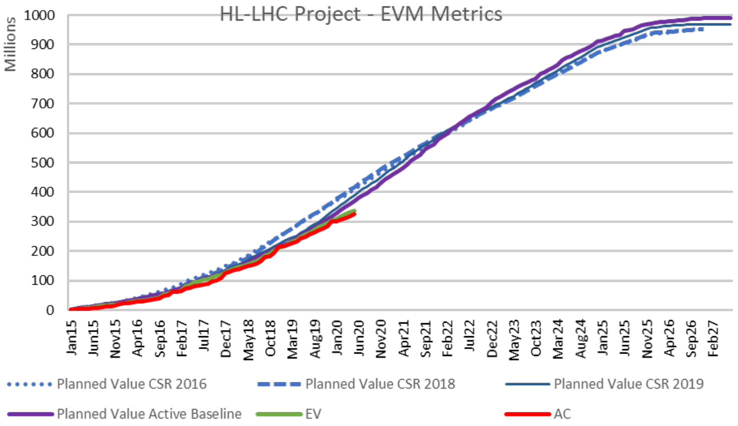

Figure 1-7: The HL-LHC construction project budget allocation as a function of time over 2015–2027, as prepared by the Budget Office for integration in the CERN Medium-Term Plan 2020–2021 with the past and present CtC (active baseline, violet curve). The earned value in June 2020 was 336 MCHF.

1.5 HL-LHC international collaboration

The LHC Luminosity Upgrade was envisioned from the beginning as being an international project. Indeed, US laboratories started to work on it with considerable resources well before CERN. In 2002–2003 a collaboration between the US laboratories and CERN established a first road map for a LHC upgrade 16 [21]. The LARP programme was then set up and approved by the US Department of Energy (DOE). In the meantime, CERN was totally engaged in LHC construction and commissioning: it could only participate in Coordinated

Accelerator Research in Europe (CARE), an EC-FP6 programme, in 2004–2008. CARE contained a modest programme for the LHC upgrade. Then two FP7 programmes (SLH-PP and EuCARD) helped to reinforce the design and R&D work for the LHC upgrade in Europe, although still at a modest level. CERN started in 2008 the project LHC luminosity upgrade phase-1, based on inner triplet quadrupoles with 120 mm aperture (vs. the 70 mm of the present LHC and 150 mm for the HL-LHC), made with Nb-Ti technology, that was stopped in 2010 when HL-LHC was established. KEK in Japan, in the framework of the permanent CERN-KEK collaboration, also engaged from 2008 in activities for the LHC upgrade. LARP remained, until 2011, the main R&D activity in the world for the LHC upgrade.

Finally, with the approval of the FP7 Design Study *HiLumi LHC* in 2011, and the maturing of the main project lines, the HL-LHC collaboration took its present form with participation of various laboratories, also from outside of Europe (KEK was formally part of FP-HiLumi and USA-LARP laboratories were associated to it). Since 2013, efforts have been launched to establish a collaboration framework for the HL-LHC project that continues beyond the EC funded FP7 Design Study and to also address the contribution of actual hardware systems (in-kind contributions). The cornerstone in these efforts is the transformation in 2016 of the US LARP program to a construction project called US HL-LHC Accelerator Upgrade Project (US-AUP). US-AUP will provide to HL-LHC half the Inner Triplet Nb_3Sn quadrupoles (Q1 and Q3 in their cryostat) and half of the crab cavities (the RFD dressed cavities). In addition to these efforts with the USA we have been able to successfully negotiate various in-kind contributions from Laboratories and Institutions in the CERN Member States (MS) and non-member states (NMS). In case of MS Institutions, the baseline is that CERN gives a financial contribution equal to 50% of the material cost of the equipment. For NMS Institution the in-kind is normally at charge of the Institutions (exception for special materials or tooling might be agreed). In addition to the collaborations for in-kinds, there are various collaborations for studies. In general, the participation to the project is expressed by signing the high-luminosity LHC MoU. Institutions that are providing an in-kind contribution are members of the HL-LHC Collaboration Board (see Section 1.6), and institution that collaborates for studies, R&D and with associated personnel are invited to the HL-LHC Collaboration Board as partners. Table 1-2 reports the list of collaborations providing in-kind contribution, design, R&D or providing associated personnel for the project.

Table 1-2: Institutions contributing to the HL-LHC project.

In-Kind	
Lancaster University, Royal Holloway University, Cockcroft Institute – ASTeC, University of Manchester University of Liverpool University of Southampton University of Oxford (UK)	
INFN-Milan-LASA, INFN Genoa (IT)	
BINP, IHEP Kurchatov Institute, PNPI (RU)	
BNL, FNAL, LBNL, SLAC (USA)	
Uppsala University (SE)	KEK (JP)
TRIUMF (CA)	PAEC (PK)
CIEMAT (ES)	IHEP CAS (CN)
University of Belgrade (RB)	

Design, R&D and Associated personnel		
National University of Mar del Plata (AR)	GSI Helmholtz Centre for Heavy Ion Research (D)	Kharkiv Institute of Physics and Technology (UA)
Universidad de Oviedo, Universidad del País Vasco, Universidad de Sevilla, Universidad Politécnica de Madrid, (ES)	Commissariat à l'énergie atomique et aux énergies, Conservatoire National des Arts et Métiers, Centre national de la recherche scientifique (FR)	University of Dundee, University of Huddersfield University of Oxford (UK)
University of Malta (MT)	Lapin Amk (FI)	University of Miskolc (HU)
Université Libre de Bruxelles (BE)	National Technical University of Athens (GR)	Norwegian University of Science and Technology (NO)
Institute of Modern Physics (IMP), Beijing University of Technology, Institute of Plasma Physics (ASIPP) (CN)	Università degli Studi di Napoli Federico II, Politecnico di Torino, Sapienza University of Rome (IT)	VNIIKP, Institut Fiziki Vysokikh Energiy, JINR - Joint Institute for Nuclear Research (RU)
Instituto Superior Técnico (PT)	Jefferson Lab (USA)	Old Dominion University (USA)
Universite de Geneve (CH)	École polytechnique fédérale de Lausanne (CH)	Vienna University of Technology (AT)
Cracow University of Technology, Institute of Nuclear Physics, AGH University of Science and Technology, Cracow University of Technology, Lodz University of Technology, National Centre for Nuclear Research NCBJ (PL)		

1.6 Governance and project structure

The HL-LHC is structured in work packages (WPs), each of them subdivided in tasks arranged in a tree-like structure, a structure inherited from the FP7-HiLumi project. In Figure 1-8 the project work package structure is shown, with names of WP Leaders and deputies as well as the main collaborators. Typically, each WP is assigned four to eight tasks. The tasks are the core of the technical work. To be noticed that L. Rossi handed over the Project Leader role to O. Bruning on 1 July 2020.

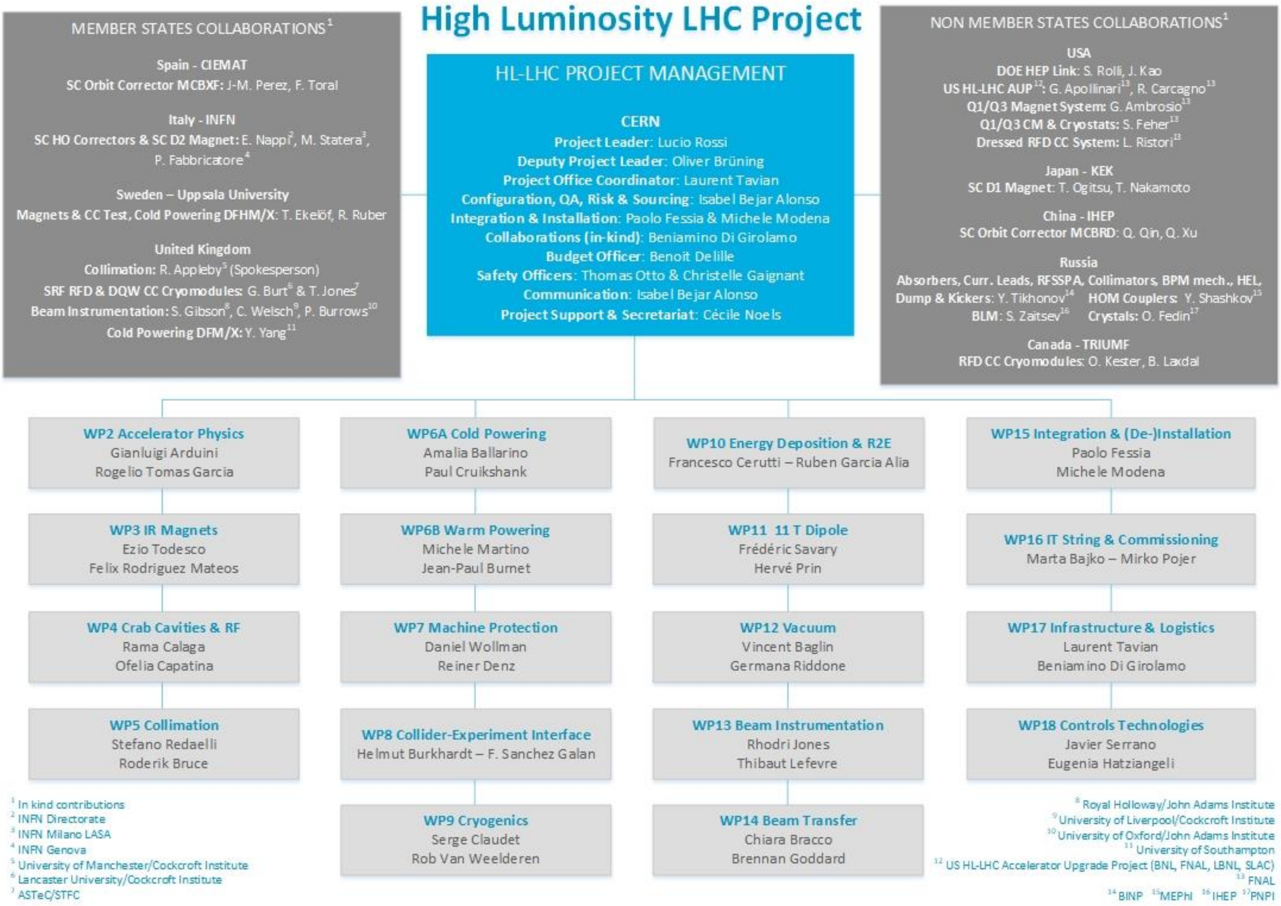

Figure 1-8: The HL-LHC project structure, with management, main collaborators and WP leaders.

The HL-LHC governance and position inside the CERN Accelerator & Technology Sector is shown in Figure 1-9. The Project management holds weekly project management meetings and a monthly special meeting to steer civil engineer works with the SMB department, and uses three main bodies to govern the project:

- HL-LHC Technical Coordination Committee that follows up on the hardware developments and prototype testing;
- HL-LHC Project Steering Committee that meets for each WP two to four times per year with the WP leader, the project office and with the implied group leaders and department management, to supervise budget and planning evolution;
- HL-LHC Coordination Group: high level interface and connection with experiments;

The Collaboration Board meets once a year and recognizes the value and importance of the new collaboration partners with concrete hardware contributions and facilitates the coordination and information flow between the partners. In addition, the HL project management is a member of the Executive Committee, which looks after decisions that will affect both the LIU and HL-LHC projects with CERN-wide relevance and of the Extended A&T Sector management board (EATSMB).

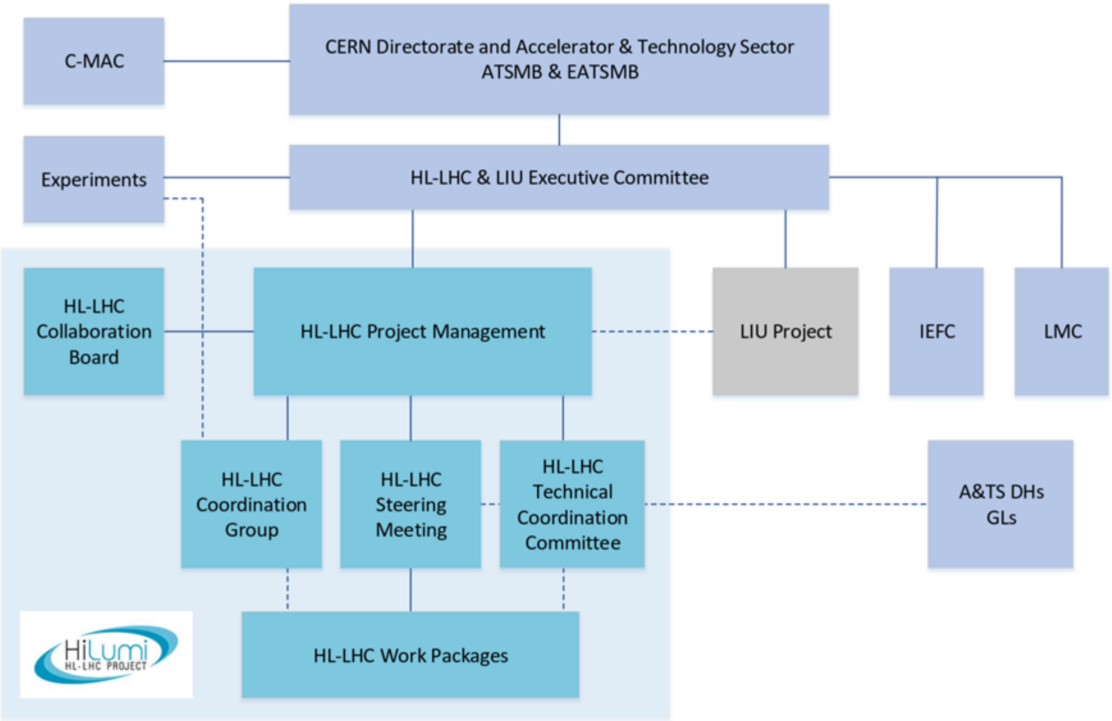

Figure 1-9. The HL-LHC organization in the global CERN Accelerator & Technology Sector structure for the construction phase.

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