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HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Deliverable Report

HiLumi LHC Technical Design Report

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HILUMI LHC

FP7 High Luminosity Large Hadron Collider Design Study

Seventh Framework Programme, Capacities Specific Programme, Research Infrastructures, Collaborative Project, Design Study

DELIVERABLE REPORT

HILUMI LHC TECHNICAL DESIGN REPORT

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Abstract:

This report contains the High Luminosity LHC Technical Design Report (TDR), which is the main deliverable of the design study. It is based on the Preliminary Design Report (Deliverable D1.5). To improve readability, this document contains a short project description, highlighting the main changes with respect to the PDR, while the full version of the new TDR document is cross-linked. It is worth noticing that now the High Luminosity LHC project has been fully approved by CERN Council (September 2015) and is now heading for construction. Installation is foreseen for 2024-25, while first commissioning is expected in 2026.

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404. HiLumi LHC began in November 2011 and will run for 4 years.

Delivery Slip

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Executive summary

The High Luminosity LHC Technical Design Report (TDR) is the main legacy of the FP7-HiLumi LHC Design Study. It is a complete description of the project, including a first preliminary description of the technical infrastructure (WP2 to WP15). Indeed this, together with WP from 7 to 17, despite that are outside of the FP7 support, are critical to the success of the whole project. Large extent is, however, left to the WP1 to WP6, the ones that are part of the FP7-HiLumi LHC Design Study, since they contain the machine layout description, the beam physics and performance together with the development of the most challenging technologies: 12 T magnets, RF crab cavities, advanced collimators, high current superconducting links.

This document is composed by a short description of the whole project, including resources (Material plus Personnel) and then crosslinking to the full TDR document.

1. INTRODUCTION

Thanks to the LHC, Europe has decisively regained world leadership in High Energy Physics (HEP), a key sector of knowledge and technology. The LHC can continue to act as catalyst for a global effort unrivalled by any other branch of science: out of the 10,000 CERN users, more than 7,000 are scientists and engineers using the LHC, half of which are from countries outside the EU.

The LHC will remain the most powerful accelerator in the world for at least the next two decades. Its full exploitation is the highest priority of the European Strategy for particle physics. This strategy has been adopted by the CERN Council, and is a reference point for the Particle Physics Strategy of the USA and, to a certain extent, Japan. To extend its discovery potential, the LHC will need a major upgrade in the 2020s to increase its luminosity (and thus event rate) by a factor of five beyond its nominal design value. The integrated luminosity goal is a ten-fold increase of the nominal design value. Since LHC is a highly complex and optimized machine, such an upgrade must be carefully studied. The necessary developments requires about 10 years of prototyping, testing and implementing. The novel machine configuration, the High Luminosity LHC (HL-LHC), will rely on a number of key innovative technologies representing exceptional technological challenges. These include among others: cutting-edge 11-12 tesla superconducting magnets; very compact with ultra-precise phase control superconducting crab cavities for beam rotation; new technology for beam collimation; and high-power superconducting links with zero energy dissipation.

HL-LHC federates efforts and R&D of a large international community towards the ambitious HL-LHC objectives and contributes to establishing the European Research Area (ERA) as a focal point of global research cooperation and a leader in frontier knowledge and technologies. HL-LHC relies on a strong participation from various partners, in particular leading US and Japanese laboratories. This participation will be required for the execution of the construction phase as a global project. In particular, the USA LHC Accelerator R&D Program (LARP) has developed some of the key technologies for the HL-LHC, such as the large aperture niobium-tin (Nb_3Sn) quadrupoles and the crab cavities. The proposed governance model is tailored accordingly and should pave the way for the organization of the construction phase.

2. HIGH LUMINOSITY LHC IN A NUTSHELL

The LHC baseline programme until 2025 is shown schematically in Figure 1. After approaching the nominal energy regime, with 13 TeV centre-of-mass energy operation in 2015, it is expected that the LHC will reach the design luminosity of 1×1034 cm-2 s-1. This peak value should give a total integrated luminosity of about 40 fb-1 per year. In the period 2015-2022 LHC will hopefully further increase the peak luminosity by exploiting upgrades during the second long shutdown LS2. Margins in the design of the nominal LHC are expected to allow, in principle, about two times the nominal design luminosity performance. The baseline programme for the next ten years is depicted in Figure 1, while Figure 2 shows the possible evolution of peak and integrated luminosity.

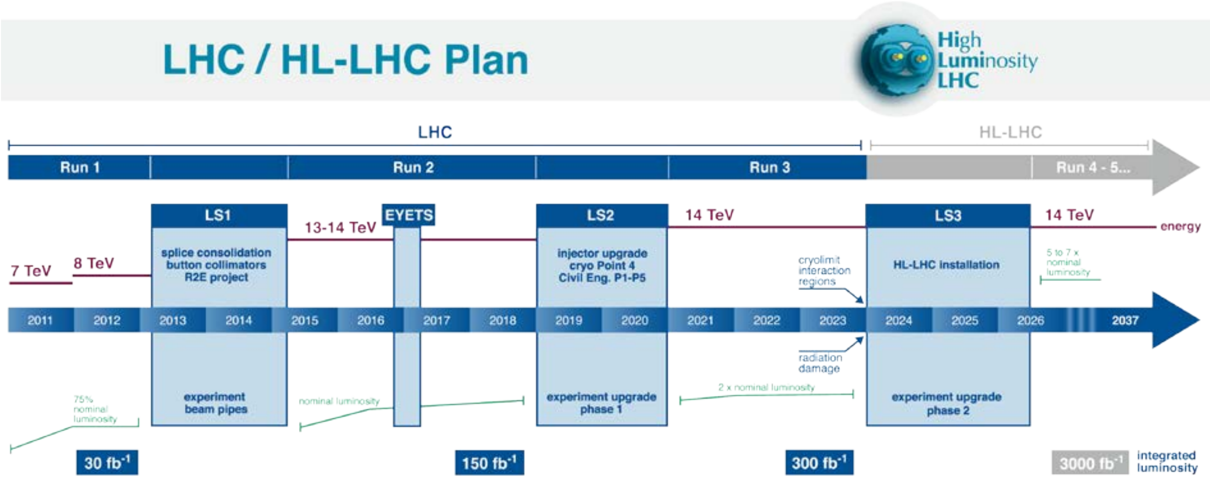

Figure 1. LHC baseline plan for the next decade and beyond showing the energy of the collisions (upper line - red) and luminosity (lower lines - green). The first long shutdown (LS1) in 2013-14 allows design parameters of beam energy and luminosity to be reached. The second long shutdown (LS2) in 2019-20, will consolidate luminosity and reliability as well as upgrade the LHC Injectors. After LS3, 2024-2026, the machine will be in the High Luminosity configuration (HL-LHC).

To maintain scientific progress and to explore its full capability, the LHC will need to have a decisive increase of its luminosity. This is why, when the CERN Council adopted the European Strategy for particle physics in 2006 [1], its first priority was agreed to be "to fully exploit the physics potential of the LHC. A subsequent major luminosity upgrade, motivated by physics results and operation experience, will be enabled by focused R&D". The European Strategy for particle physics has been integrated into the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap of 2006, as has the update of 2008 [2]. The priority to fully exploit the potential of the LHC has been recently confirmed as first priority among the "High priority large-scale scientific activities" in the new European Strategy for particle physics – Update 2013 [3]. This update was approved in Brussels on 30 May 2013 with the following wording: "Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030".

The importance of the LHC luminosity upgrade for the future of High Energy Physics has been also recently re-affirmed by the May 2014 recommendation by the Particle Physics Project Prioritization Panel (P5) to the High Energy Physics Advisory Panel (HEPAP), which in turn advises the US Department of Energy (DOE) [4]. The recommendation, a critical step in updating the USA strategy for HEP, states the following: "Recommendation 10: The LHC upgrades constitute our highest-priority near-term large project."

In Japan, the 2012 report of a subcommittee in the HEP community concluded that an e+e- linear collider and a large scale neutrino detector be the core projects in Japan, with the assumption that the LHC and its upgrade are pursued de facto. The updated KEK roadmap in 2013 states that "The main agenda at LHC/ATLAS is to continually participate in the experiment and to take a proactive initiative in upgrade programs within the international collaboration at both the accelerator and detector facilities."

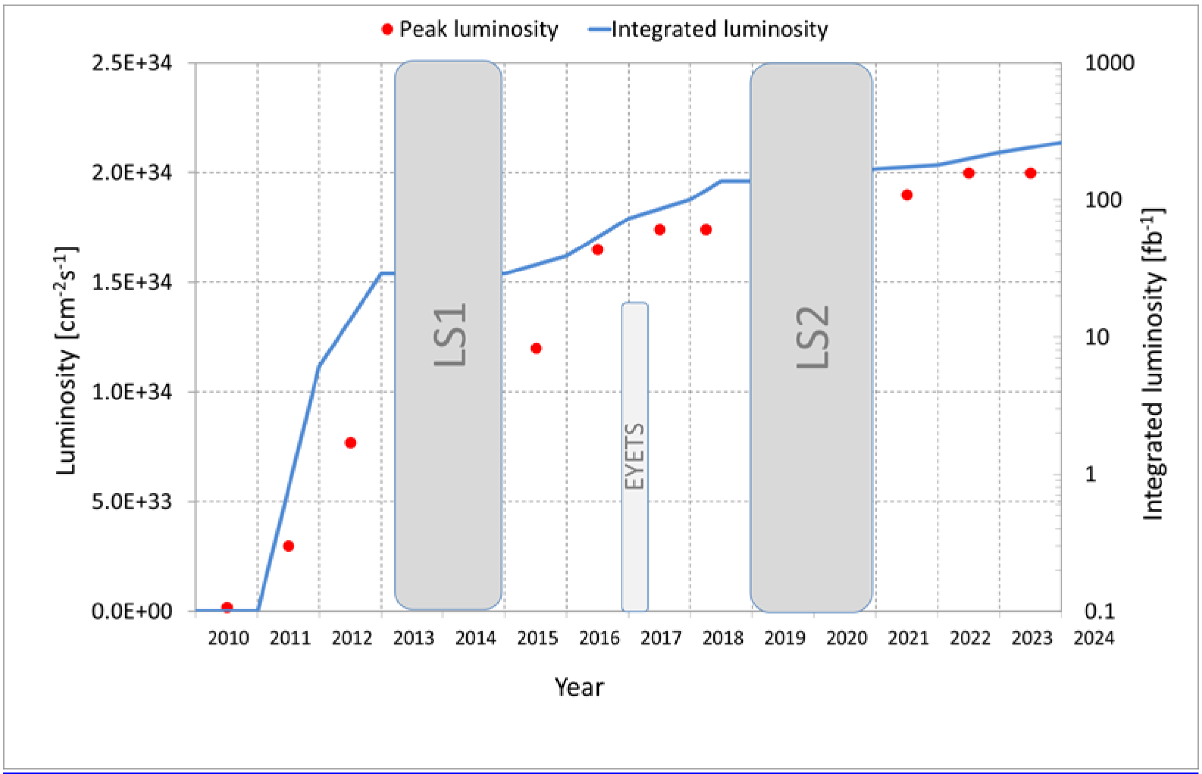

Figure 2. LHC luminosity plan for the next decade, both peak (red dots) and integrated (blue line). Main shutdown periods are indicated.

Following these supports, the ATLAS-Japan group has been making intensive R&D on the detector upgrades and the KEK cryogenic group has started the R&D of the LHC separation dipole magnet.

In this context, at the end of 2010 CERN instituted the High Luminosity LHC (HL-LHC) project [5]. Started as a design study, after the approval of CERN Council of 30 May 2013 and the insertion of the budget in the CERN Medium Term Plan approved by Council in September 2013 and then revised in June 2014, HL-LHC has become the CERN's major construction project for the next decade. Following the Cost & Schedule (C&S) review held on 9-11 march at CERN, the new budget profile, with full Cost-to-Completion as endorsed by the C&S review, was inserted in the MTP2015 and approved by CERN Council in September 2015 (the budget profile beyond the MTP2015, for 2021-26, was included for information).

The main objective of the High Luminosity LHC design study is to determine a set of beam parameters and the hardware configuration that will enable the LHC to reach the following targets:

a. A peak luminosity of **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing:
b. An integrated luminosity of 250 fb^{-1} per year with the **goal of 3000 fb^{-1}** in about a dozen years after the upgrade. This integrated luminosity is about ten times the expected luminosity reach of the first twelve years of the LHC lifetime.

The overarching goals are the installation of the main hardware for HL-LHC and the commissioning of the new machine configuration during LS3, scheduled for 2024-2026, while taking all actions to assure a high efficiency in operation until 2035-40.

All equipment for the HL-LHC is being designed with a margin of 50% with regard to the luminosity reach, both as peak value and as integrated one. Taking profit of this, the concept of *ultimate parameters* has been defined. By exploiting the margins one should be able to push the HL-LHC machine performance to an *ultimate levelled luminosity of about 7-7.5 10^{34} cm^{-2} s^{-1}*. This would imply an increase in the pile-up (number of events in the same bunch crossing) in the general purpose detectors to up to 200. The increased luminosity level should allow the delivery of 300-350 fb^{-1}/year. In terms of total integrated luminosity, *an ultimate value of about 4000 fb^{-1}* is defined. It must be said that while at a first sight there are no show-stoppers to these enhanced performance levels, the ultimate parameters have not been considered in the same depth as the nominal parameters. Therefore, they will be thoroughly scrutinized for the next version of the technical design report.

All the hadron colliders in the world before the LHC have produced a combined total integrated luminosity of about 10 fb^{-1}. The LHC delivered nearly 30 fb^{-1} by the end of 2012 and should reach 300 fb^{-1} in its first 13-15 years of operation. The High Luminosity LHC is a major, extremely challenging, upgrade. For its successful realization, a number of key novel technologies have to be developed, validated and integrated. The first step of the project, the Design Study under the auspices of EC-FP7 with the nickname of **HiLumi LHC**, was approved with full score by EC in 2011. FP7-HiLumi LHC It has been instrumental in initiating a new global collaboration for the LHC matching the spirit of the worldwide user community of the LHC experiments.

The High Luminosity LHC project is working in close collaboration with the CERN project for the LHC Injector complex Upgrade (LIU) [12], the companion ATLAS and CMS upgrade projects of 2018-19 and 2023-25 and the upgrade foreseen in 2018-19 for both LHCb and ALICE.

2.1. LUMINOSITY

The (instantaneous) luminosity L can be expressed as:

$$L = \gamma \frac{n_b N^2 f_{rev}}{4\pi \beta^* \varepsilon_n} R; \qquad R = 1/\sqrt{1+\frac{\theta_c \sigma_z}{2\sigma}} \qquad \textbf{(2-1)}$$

γ is the proton beam energy in unit of rest mass

n_b is the number of bunches per beam: 2808 (nominal LHC value) for 25 ns bunch spacing

N is the bunch population. N $_{\text{nominal 25 ns}}$: 1.15×10^{11} p (⇒0.58 A of beam current at 2808 bunches)

f_{rev} is the revolution frequency (11.2 kHz)

β^* is the beam beta function at the collision point (nominal design 0.55 m)

ε_n is the transverse normalized emittance (nominal design: 3.75 μm)

R is a luminosity geometrical reduction factor (0.85 at a β^* *of* 0.55 m of, down to 0.5 at 0.25 m)

θ_c is the full crossing angle between colliding beam (285 μrad as nominal design)

σ, σ_z are the transverse and longitudinal r.m.s. sizes, respectively (nominally 16.7 μm and 7.55 cm respectively)

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

2.2. PRESENT LUMINOSITY LIMITATIONS AND HARDWARE CONSTRAINTS

There are various expected limitations to an increase in luminosity, either from beam characteristics (injector chain, beam impedance and beam-beam interactions in the LHC) or from technical systems. Mitigation of potential performance limitations arising from the LHC injector complex are addressed by the previously mentioned LIU project, which should be completed in 2020 (LS2). Any potential limitation coming from the LHC injector complex put aside, it is expected that the present LHC will reach a performance limitation from the beam current, from cleaning efficiency with 350 MJ beam stored energy, from e-clouds effects, from the maximum available cooling in the triplet magnets, from the magnet aperture (β^* limit) and from the acceptable pile-up level. The ultimate value of bunch population (1.15×10^{11} protons, with 25 ns bunch spacing) with the present LHC should enable a peak luminosity of around 2×10^{34} $cm^{-2}s^{-1}$ to be reached. Any further performance increase of the LHC will require significant hardware and beam parameter modifications with respect to the design LHC configuration.

Before discussing the new configuration it is useful to recall the systems that need to be changed, and possibly improved, because they become vulnerable to breakdown and accelerated aging, or because they may become a bottleneck for operation in a higher radiation environment. This goes well beyond the on-going basic consolidation.

Low-β Triplet Magnets: After about 300 fb^{-1} some components of the low-β (or 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 400-700 fb^{-1}, but some corrector magnets of nested type are likely to fail already at 300 fb^{-1}. Actual damage must be anticipated because the most likely failure mode is through sudden electric breakdown, entailing serious and long repairs. Thus the replacement of the triplet must be envisaged before damage occurs. Replacement of the low-beta triplet is a long intervention, requiring one to two years shutdown and must be coupled with major detector upgrades.

Cryogenics: To increase intervention flexibility and machine availability it is planned to install a new cryogenics plant for a full separation between SCRF accelerating cavities and arc magnets cooling. In the long term, the cooling of the inner triplets and matching section magnets must be separated from the magnets of the arcs. This would avoid the need to a warm-up an entire arc in the case of triplet region intervention.

Collimation: The collimation system has been designed for the first operation phase of LHC. The present system was optimized for robustness and will need an upgrade that takes in account the need for the lower impedance required for the planned increased beam intensities.

A new configuration will also be required to protect the new triplets in IR1 and IR5. Also requiring special attention are the Dispersion Suppressor (DS) regions, where a leakage of off-momentum particles into the first and second main superconducting dipoles has been already identified as a possible LHC performance limitation. The most promising concept is to substitute an LHC main dipole with 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 room gained is sufficient for installing special collimators.

R2E and SC links for remote powering of cold circuits*:* considerable effort is under way to study how to replace the radiation sensitive electronic boards of the power converter system with radiation-hard cards. A complementary solution is also being pursued for special zones. This would entail installing the power converters and associate DFBs (electrical feed-boxes, delicate equipment at present in line with the continuous cryostat) outside of the tunnel, solving also the problem of lack of space for all new, larger, electrical power converters. LHC availability should be improved by means of the relocation. Installation of power converters to distant locations is convenient thanks to a novel technology: superconducting links (SCLs) made from HTS (YBCO or Bi-2223) or MgB_2 superconductors.

QPS, machine protection and remote manipulation*:* Other systems will potentially become problematic, along with aging of the machine and the radiation level that come with higher performance levels of 40 to 60 fb^{-1} per year:

Quench Protection System of the superconducting magnets, based on a design that is almost 20 years old.

Machine protection: improved robustness to mis-injected beams, to kickers sparks and asynchronous dumps will be required. The kicker system is, with collimation and the injection beam stopper, the main shield against severe beam induced damage. The kicker systems, along with the collimation system will need serious renovation after 2020 (some components even earlier).

Remote manipulation: the level of activation from 2025 onwards, and perhaps even earlier, requires a careful study and the development of special equipment to allow replacing collimators, magnets, vacuum components etc., according to as low as reasonably achievable principle (ALARA). While full robotics is difficult to implement, given the conditions in the tunnel, remote manipulation, augmented reality and supervision are the key to minimizing the radiation doses sustained during interventions.

2.3. LUMINOSITY LEVELLING, 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 "a-priori" a limitation of the peak luminosity. The consequence is that the HL-LHC operation will have to rely on luminosity levelling. As shown in Figure 3 left, the luminosity profile without levelling quickly decreases from the initial peak value due to "luminosity burn-off" (protons consumed in the collisions). The high luminosity collider is designed to operate with a constant luminosity at a value below the virtual maximum luminosity. The average luminosity achieved is almost the same as that without levelling, see Figure 3 right. However the advantage is that the maximum peak luminosity is lower.

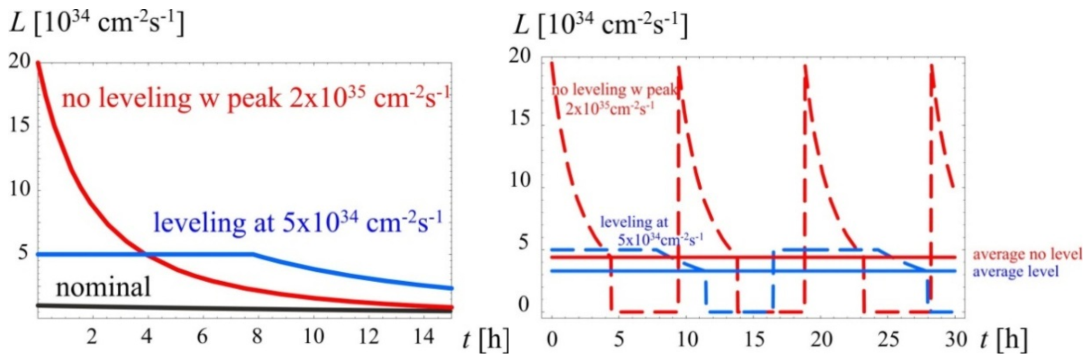

Figure 3. Left: Luminosity profile for a single long fill: starting at nominal peak luminosity (black line), with upgrade no levelling (red line), with levelling (blue line). Right: luminosity profile with optimized run time, without and with levelling (blue and red dashed lines), and average luminosity in both cases (solid lines).

Because of the levelled luminosity limit, and to maximize the integrated luminosity one needs to maximise the fill length and assure average fill lengths that are longer than the levelling time. The fill theoretical length can be maximised by maximizing the injected beam current. Other key factors for maximizing the integrated luminosity and obtaining the required 3 fb^{-1}/day (see Figure 4) are a short average machine turnaround time, an average operational fill length which exceeds the luminosity levelling time, and good overall machine efficiency. The machine efficiency is essentially the available time for physics after downtime for fault recovery is taken into account. Closely related is the physics efficiency – the fraction of time per year spent actually providing collisions to the experiments. For the integrated luminosity the efficiency counts almost as much as the virtual peak performance.

The HL-LHC with 160 days of physics operation a year needs a physics efficiency of about 50% to reach its goal. The overall LHC efficiency during the 2012 run, without luminosity levelling, was around 37%. The requirement of an efficiency higher than the one of the present LHC, with a (levelled) luminosity five times the nominal one, will be a real challenge. The project must foresee a vigorous consolidation for the high intensity and high luminosity regime: the High Luminosity LHC must also be a high availability LHC.

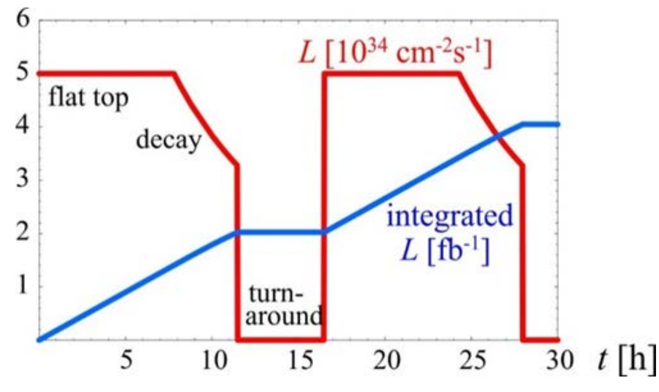

Figure 4. Luminosity cycle for HL-LHC with levelling and a short decay (optimized for integrated luminosity).

2.4. HL-LHC PARAMETERS AND MAIN SYSTEMS FOR THE UPGRADE

Table 1 lists the main parameters foreseen for the high luminosity operation. The 25 ns bunch spacing with the highest possible number of bunches is the baseline operation mode; however, a special scheme of 8 bunches followed by 4 empty bunches (8b4e) all 25 ns spaced, is kept as a possible alternative in case the e-cloud or other unforeseen effects undermine the nominal

25 ns performance. A slightly different parameter set at 25 ns (BCMS: Bach Compression and beam Merging Scheme) with very small transverse beam emittance is also shown and might be interesting for the HL-LHC operation in case the operation with high beam intensities results in unforeseen emittance blow-up.

An upgrade should provide the potentiality of performance over a wide range of parameters, and eventually the machine and experiments will find the best practical set of parameters in actual operations.

Beam current and brightness: 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; Cryogenics; Kickers; Vacuum; beam diagnostics; QPS etc. Radiation effects aside, all systems have been designed in principle for Ibeam= 0.86 A, the so-called “ultimate” beam current. However the ability to go to the ultimate limit is still to be experimentally demonstrated and the HL-LHC will need to go 30% beyond the ultimate beam intensities with 25 ns bunch spacing.

For HL-LHC there is a need to increase the beam brightness, a beam characteristic that must be maximized at the beginning of the beam generation and then preserved throughout the entire injector chain and in LHC itself. The LIU project has the primary objective of increasing the number of protons per bunch by a factor two above nominal design value while keeping the emittance at the present low value.

β* and cancelling the reduction factor R: A classical route for a luminosity upgrade is to reduce β* by means of larger aperture and higher field low- β triplet quadrupoles. However a reduction in β* values implies not only larger beam sizes in the triplet magnets but also an increase in crossing angle if the beam separation in the common part of the machine is kept at a constant value in terms of normalized beam separation (beam separation divided by the rms beam size). The increased crossing angle in turn requires even larger aperture triplet magnets, a larger aperture D1 (first separation dipole) and further modifications of the matching section. It also reduces the luminous region size and thus the gain in peak luminosity.

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 in the nominal LHC the practical limit for β* is 30-40 cm cf. the nominal 55 cm. However, a novel scheme called Achromatic Telescopic Squeeze (ATS) [13] 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 a flat optics with a β* as low as 5 cm in the plane perpendicular to the crossing plane could be realized. For such a β* reduction the low-β triplet quadrupoles need to double their aperture, and provide a peak field 50% above the present LHC. This implies the use of new, advanced, superconducting technology based on Nb_3Sn.

As above mentioned, use of very small β* requires a larger crossing angle. The drawback of very small β* is that it further reduces the values of the geometrical luminosity reduction factor, R. In Figure 5 the reduction factor values are plotted vs. β* values.

Table 1: HL-LHC parameter list

HL-LHC Parameters V4.2 (Last updated 22-September-2015)

Parameter	**Nominal LHC (design report)**	**HL-LHC 25ns (standard)**	**HL-LHC 25ns (BCMS)** [9]	**HL-LHC 8b+4e** [12]
Beam energy in collision [TeV]	7	7	7	7
N_b	1.15E+11	2.2E+11	2.2E+11	2.3E+11
n_b	2808	2748	2604	1968
Number of collisions in IP1 and IP5 [1]	2808	2736	2592	1960
N_{tot}	3.2E+14	6.0E+14	5.7E+14	4.5E+14
beam current [A]	0.58	1.09	1.03	0.82
x-ing angle [μrad]	285	590	590	554 [10]
beam separation [σ] [11]	9.4	12.5	12.5	12.5 [10]
β^* [m]	0.55	0.15	0.15	0.15
ε_n [μm]	3.75	2.50	2.50	2.20
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	13.1
IBS longitudinal [h]	61 -> 60	20.4	20.4	17.6
Piwinski parameter	0.65	3.14	3.14	3.14
Total loss factor R0 without crab-cavity	0.836	0.305	0.305	0.304
Total loss factor R1 with crab-cavity	(0.981)	0.829	0.829	0.828
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03	3.3E-03	3.9E-03
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02	1.1E-02	1.3E-02
Peak Luminosity without crab-cavity [cm^{-2} s^{-1}]	1.00E+34	7.18E+34	6.80E+34	6.38E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm^{-2} s^{-1}]	(1.18E+34)	19.54E+34	18.52E+34	17.40E+34
Events / crossing without levelling and without crab-cavity	27	198	198	246
Levelled Luminosity [cm^{-2} s^{-1}]	-	5.00E+34 [5]	5.00E+34	3.63E+34
Events / crossing (with leveling and crab-cavities for HL-LHC) [8]	27	138	146	140
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.25	1.31	1.28
Leveling time [h] (assuming no emittance growth) [8]	-	8.3	7.6	9.5
Number of collisions in IP2/IP8	2808	2452/2524 [7]	2288/2396	1163/1868
N_b at LHC injection [2]	1.20E+11	2.30E+11	2.30E+11	2.40E+11
n_b / injection	288	288	288	224
N_{tot} / injection	3.46E+13	6.62E+13	6.62E+13	5.40E13
ε_n at SPS extraction [μm] [3]	3.40	2.00	< 2.00 [6]	1.70

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 down to 1.4 μm have already been achieved at LHC injection which might be used to mitigate excessive emittance blow-up in the LHC during injection and ramp.

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.

8 The total number of events/crossing is calculated with an inelastic cross-section of 85 mb (also for nominal), while 100 mb is still assumed for calculating the proton burn off and the resulting levelling time.

9 BCMS parameters are only considered for injection and as a backup parameter set in case one encounters larger than expected emittance growth in the HL-LHC during injection, ramp and squeeze.

10 The crossing angle for the 8b+4e alternative could be reduced down to about 400 μrad (9 σ) thanks to the lower number of long ranges.

11 Minimum normalized long-range beam-beam separation at minimum β*.

12 The 8b+4e variant represents a back-up scenario for the baseline 25ns operation in case of e-cloud limitations. The parameters are still evolving but are stated for the sake of performance reach comparison.

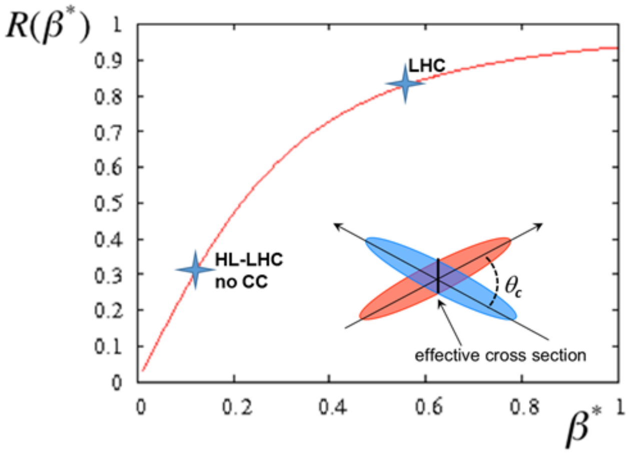

Figure 5. Behaviour of geometrical luminosity reduction factor vs. β for a constant normalized beam separation in the common beam pipe with the indication of two operational points: nominal LHC and HL-LHC. The sketch of bunch crossing shows the reduction mechanism.*

Various methods can be employed to counteract at least partially 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 collide effectively head on, overlapping perfectly at the collision points, as illustrated in Figure 6. 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, as shown by the HL-LHC operational point of Figure 6. While the primary function of the crab cavities is to boost the virtual peak luminosity, they can also be used in combination with dynamic β^* variation for luminosity levelling during the fill. Actually, this would not only allow the control of the instantaneous luminosity but also the optimization of the size of the luminous region and thus the pileup density through the fill. Finally, the crab cavities can be used to tilt the bunches in a direction perpendicular to the plane of crossing, providing pile-up mitigation and an additional handle for luminosity levelling through the so called “crab-kissing” scheme [14].

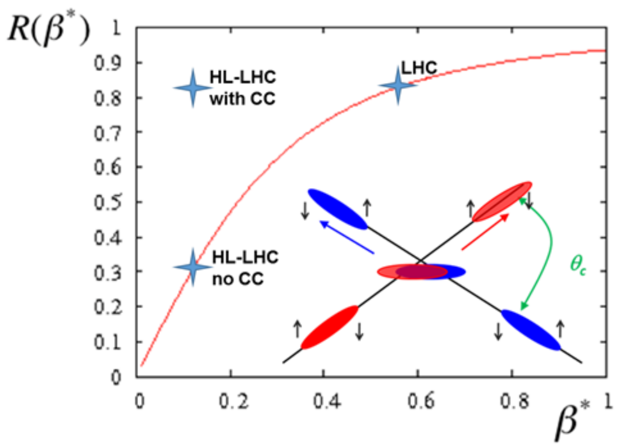

Figure 6. Geometrical reduction factor R vs β showing the effect of crab cavity (CC). The crab cavity beam manipulation is depicted in the bottom right insect (small arrows indicate the torque on the bunch generated by the transverse RF field).*

A description of the hardware configuration and lay-out would go beyond the scope of the present paper and we refer to the Preliminary Design Report [15]. Here we report a schematic view of the most critical zone, the Insertion Region around the high luminosity detectors, ATLAS and CMS, see Figure 7. In total about 1.2 km of the most complex zone of the LHC will be entirely renovated.

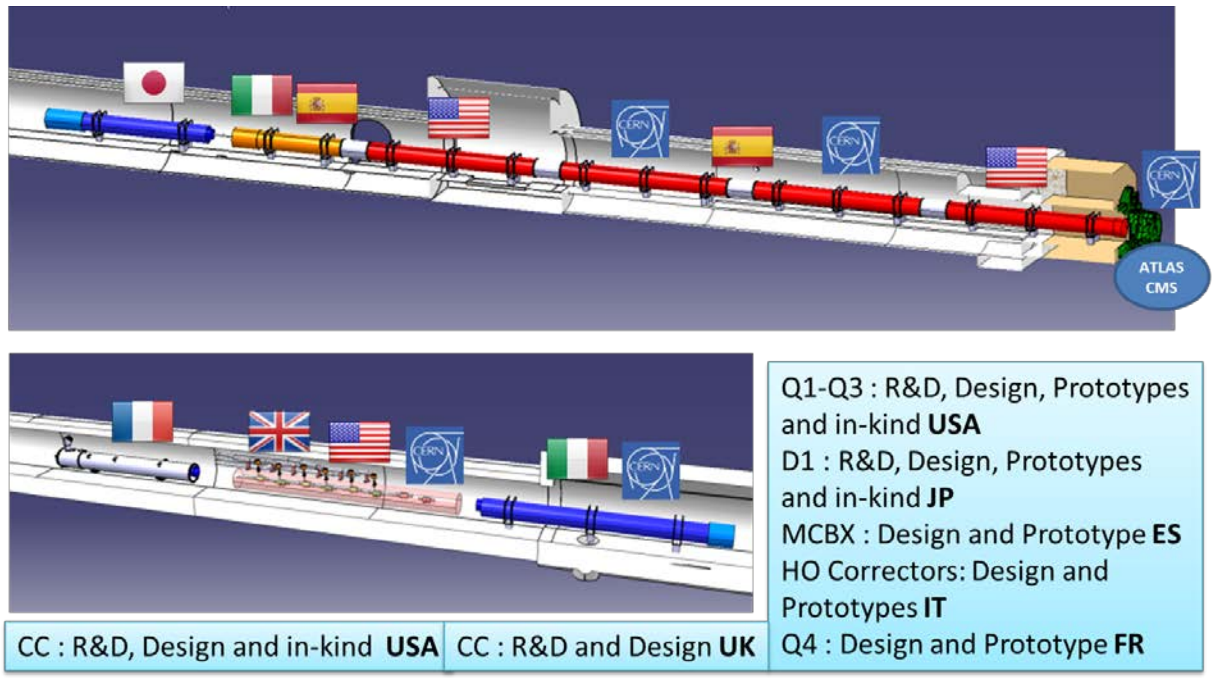

Figure 7. Schematic view of the new Insertion Region on left side of either ATLAS or CMS. Interaction Region (top picture) features: 4 low-β triplet quadrupoles (Q1-Q2a-Q2b-Q3, red); one corrector magnet module (orange); D1 separating dipole (blue). Matching Section (bottom figure) features: D2 recombination dipole (blue); crab cavity cryo-modules (pink); Q4 quadrupole (white).

Given the yearly and long-term operations schedule, the target of 3000 fb^{-1} by the mid-2030s is very challenging. If the performance of the HL-LHC can go beyond the design levelled luminosity value of $L_{peak} = 5\times10^{34}$ $cm^{-2}s^{-1}$ then these targets become more accessible. Indeed, all systems will be designed with some margin. If the behaviour of the machine is such as to allow the utilization of these margins, and if the upgraded detectors will accept a higher pile-up, up to 200, then the performance could eventually reach 7.5×10^{34} $cm^{-2}s^{-1}$ with levelling (see above for ultimate parameters). This would allow 3000 fb^{-1} to be obtained by 2035, as shown in Figure 8.

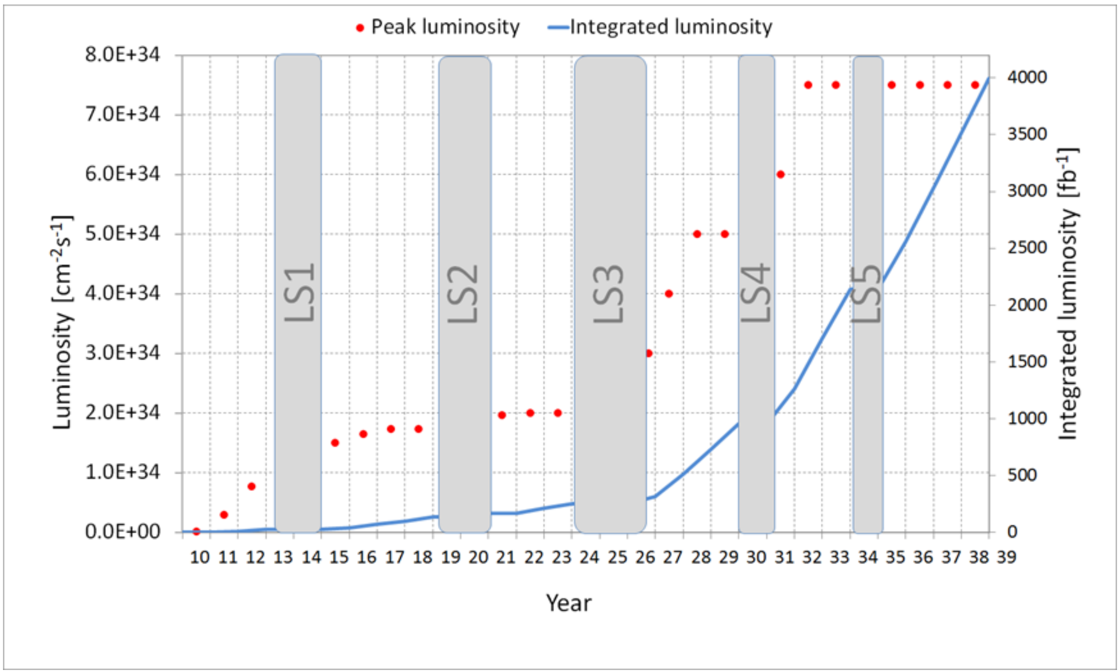

Figure 8. Forecast for peak luminosity (red dots) and integrated one (blue line) in the LHC and HL-LHC operation, for the case of ultimate HL-LHC parameters (plot by M. Lamont). Note that after LS4 the proton physics time has been maximized (from 160 days to 200 and finally 220 days/year)

2.5. PLAN AND COST

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 (so-called Phase-II upgrade). However, a few items like the new cryogenic plant for P4 and the 11 T dipole for DS collimation in P2 (for ions) would be already installed during LS2. LS2 will be also critical to advance civil engineering works and start preparation of the technical infrastructure.

The HL-LHC schedule is based on the following milestones, see Figure 9:

– 2014: Preliminary Design Report (PDR)

– 2015: First C&S review

– 2015: End of design phase, release of the first Technical Design Report (TDR-v0) with identification of Technical Infrastructure

– 2016: Proof of main hardware components on test benches

– 2016: second C&S review

– 2017: Testing of prototypes and release of TDR_v1 (TDR in final version, for construction)

– 2018-2023: Construction and test of long lead time hardware components (e.g. magnets, crab cavities, SC links, and collimators)

– 2018: start civil engineer construction (large pit)

– 2019-2020: LS2 – Modification of cryo-plant in P4, DS collimators in P2, underground civil engineering (and technical infrastructure

– 2021-2023: String test of Interaction Region elements (Low-β Triplet, dipole D1, Corrector Package, SC links, Powering circuit)

– 2024-2026: LS3 – Main installation (new magnets, crab cavities, cryo-plants, collimators, absorbers, etc.) and commissioning.

Figure 9. Schematic representation of the HL-LHC timeline.

The preliminary cost-to-completion (CtC) of the HL-LHC project was evaluated in 2011 to be about 830 MCHF for Material (CERN accounting), In view of the C&S review, and following the decision to have two large 300 m long galleries undergrounds, the amount has been re-evaluated to 954 MCHF in spring 2015. The increase mainly occurred because of the Civil Engineer and Technical Infrastructure, whose configuration was deeply different, and much lighter, at the beginning of the project and because of the need of associated personnel to cope with peak need of labor. The evaluation of staff personnel requirements amounts to more than 1600 FTE-y, spread over the ten years of the project. The cost-to-completion does not include non-baseline systems such as the long-range beam-beam compensators and the RF harmonic system and the related infrastructures.

Today the CERN budget attributes about 954 MCHF for the HL-LHC project for Materials until 2026, with the profile shown in Figure 10, with certain assumptions of in-kind contributions from both the USA and Japan. Thorough investigation of potential synergy with the LHC consolidation project together, has allowed to identify the LHC equipment or systems whose consolidation is strictly necessary in view of HL-LHC, whose total value amounts to about 83 MCHF, with the profile indicated in Figure 10.

Following C&S review, the Crab Cavity system has been staged: installation of half of the CC cryomodules is foreseen for LS4. Impact of this staging on luminosity profile of Figure 8 is minor and will be precisely quantified in future.

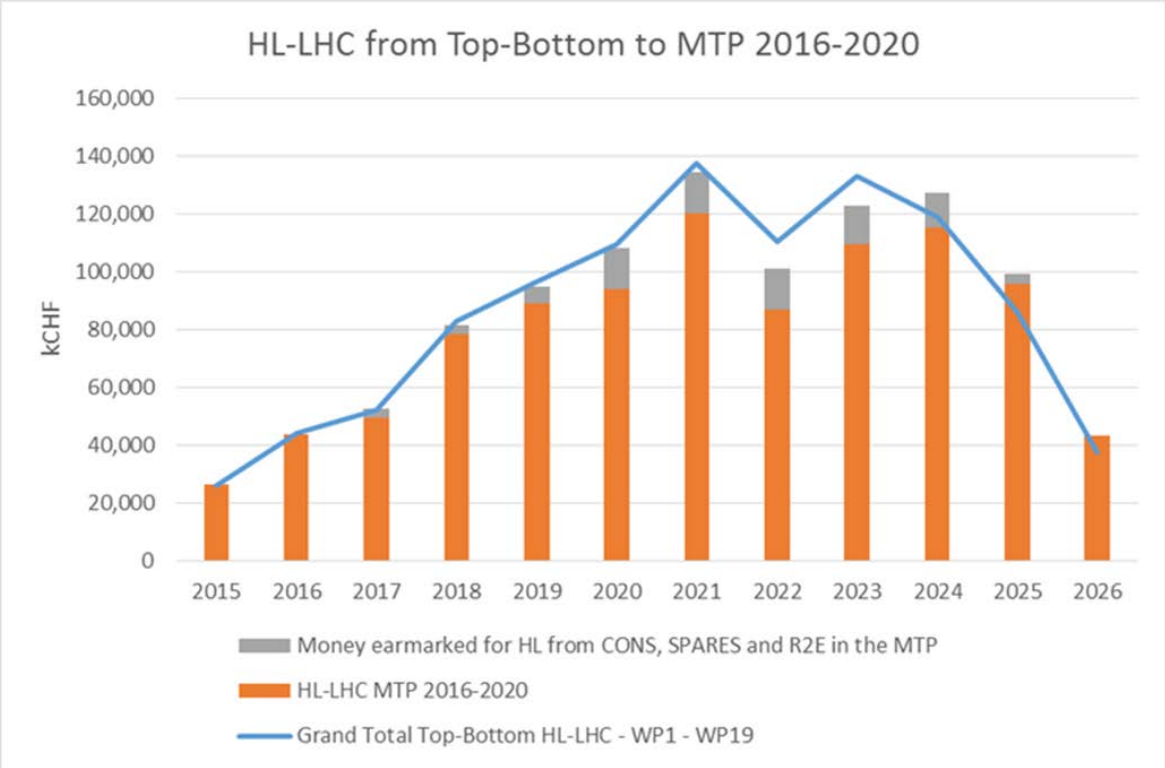

Figure 10. Budget allocation 2015 – 2026 The continuous line is the need for each Work Package. The Histogram show the budget allocated to HL-LHC and the budget allocated in the Consolidation Project dedicated to the consolidation of existing equipment that is deemed necessary for HL-LHC. The orange bars (HL-LHC proper) sums to 954 MCHF, while the grey ones (Consolidation for HL-LHC) sum up to 84 MCHF, for 1054 MCHF of total budget.

3. THE INTERNATIONAL COLLABORATION

The LHC Luminosity Upgrade was conceived from the beginning to be even more international than the LHC machine construction, since US laboratories started to work on it with considerable resources well before CERN. In 2002-2003 collaboration between the US laboratories and CERN established the route for a machine upgrade [7]. The program LARP (LHC Accelerator Research Program) was then setup and approved by DOE, see section 3.2. In the meantime, CERN was totally engaged in the LHC construction and commissioning: it could only participate in CARE, an EC-FP6 program, in 2004-2008. CARE contained a modest program for the LHC upgrade. Then two EC-FP7 programs (SLHC-PP and EuCARD) helped to reinforce the design and R&D work for the LHC upgrade in Europe, although still at a modest level. KEK in Japan, in the frame of the permanent CERN-KEK collaboration, also engaged in a basic and limited activity for the LHC upgrade from 2008. LARP remained until 2011 the main R&D activity in the world for the LHC upgrade.

Finally, with the approval of the EC-FP7 Design Study HiLumi LHC in 2011, and the maturing of the main project lines considered in Section 1, the collaboration for HL-LHC took the present form. It is worth noticing that FP7-HiLumi LHC covers only the design of a few systems, given the limited amount of funding in such a program. It has however allowed the formation and structuring of a European participation to the LHC Upgrade from the very beginning of the project. In 2014, CEA (Saclay, FR), INFN (Milano and Genova, IT) and

CIEMAT (Madrid, ES), have signed a further collaboration agreement to carry out design, engineering and prototyping work for HL-LHC magnets in addition to the FP7-EC commitment. In all three cases, the CERN funding for the activities is approximately 50%, the rest being supported by the collaborating institutes. In Figure 11 a schematic indicating the various collaboration branches, with timeline, is shown.

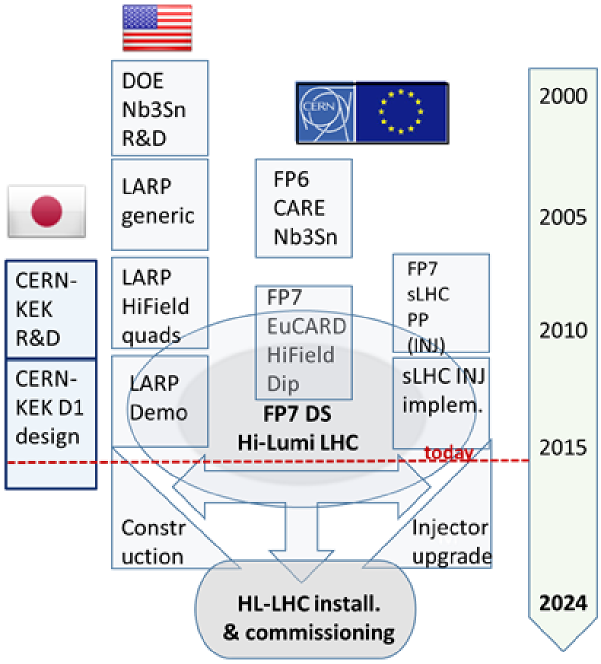

Figure 11. Timeline of the various collaboration branches, converging toward the luminosity upgrade of the LHC.

3.1. THE FP7 HILUMI LHC COLLABORATION

The "FP7 High Luminosity Large Hadron Collider Design Study", in short "HiLumi LHC" proposal was submitted on November 2010 to the EC Seventh Framework Programme. Approved with a full score of 15/15 it has been fully funded by EC. The contract was signed by the fifteen partners (beneficiaries). KEK is a partner without EC funding - all their funding is internal. The U.S. laboratories were part of the proposal, without EC funding, but then for various reasons (mainly related to IP issues) they could not sign the FP7-HiLumi LHC Consortium Agreement, thus they are external associates with no formal obligations. In practice U.S.-LARP is excellently coordinated with FP7-HiLumi (see section on "governance") and the project heavily relies on LARP to reach the project goals.

The mechanism of FP7 is such that each of the fifteen European Institutions that are members of HiLumi LHC has to match the EC contribution with its own funding. In the case of FP7-HiLumi the matching funds equal the EC funds: each EU Institute receives 50% of the total cost (including overheads). The exception is CERN that receives only 17% of its total cost, mainly for management and coordination. In Figure 12 the funding mechanism is explained. Given the success of the evaluation, see above, the project was ranked first in its category and was financed at 100% of the request, with an EU contribution of M€4.9.

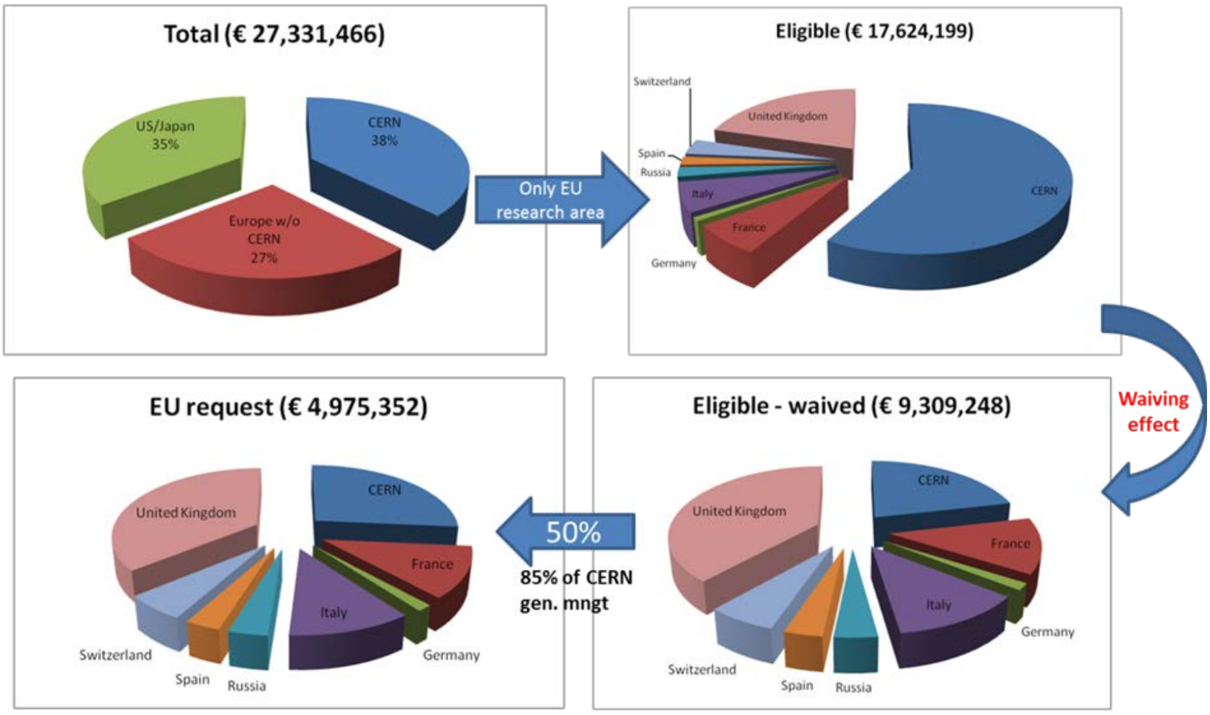

Figure 12. Top left: total estimation of the cost of the design study, subdivided by USA and Japan, EU Institutes and CERN. Top Right: total cost with USA and Japan removed (i.e. only costs that are eligible for funding by the EC). Bottom right: effect of CERN waiving the cost for technical works (recognizing that HL-LHC is part of the core CERN program financed via normal budget), while keeping the extra cost generated by the management and coordination of the project. This is the total cost declared to the E.C. Bottom right: cost claimed to EC: 50% of the declared cost (eligible cost reduced by CERN waiving action).

In Figure 13 the list of the fifteen FP7-HiLumi institutions is shown, followed by the list of the five U.S. collaborating institutes.

Short Name	Country	Logo
CERN	Geneva Switzerland	
CEA	Saclay France	
DESY	Hamburg Germany	
INFN	Frascati Italy	
CSIC	Madrid Spain	
EPFL	Lausanne Switzerland	
SOTON	Southampton United Kingdom	
RHUL	London United Kingdom	

Short Name	Country	Logo
STFC*	Daresbury United Kingdom	
ULANC*	Lancaster United Kingdom	
UNILIV*	Liverpool United Kingdom	
UNIMAN*	Manchester United Kingdom	
HUD	Huddersfield United Kingdom	
KEK	Tsukuba Japan	
BINP	Novosibirsk Russia	

*Members of Cockcroft Institute

Short Name	Country	Logo	
BNL	Upton, NY USA	BROOKHAVEN NATIONAL LABORATORY	LARP
FNAL	Batavia, IL USA	Fermilab	
LBNL	Berkeley, CA USA	BERKELEY LAB	
SLAC	Menlo Park, CA USA	SLAC	
ODU	Norfolk, VA USA	OLD DOMINION UNIVERSITY	

Figure 13. Table of the fifteen members ("beneficiaries") of the FP7 HiLumi LHC design study and of the five U.S.-LARP laboratories that are associated with the project.

3.2. U.S.-LARP

The U.S.-LARP (LHC Accelerator R&D Program) was initiated by the U.S. Department of Energy (DOE) in 2003 to participate in the commissioning of the US-built interaction region triplets by bringing together and coordinating resources from the 4 U.S. HEP laboratories (BNL, FNAL, LBNL and SLAC) with the inclusion of some universities as the program evolved. The program focused - from the very beginning - on the design of improved focusing quadrupoles for the LHC low-β insertion regions, finding a synergy with the various DOE High Field Magnet (HFM) R&D programs at the participating Laboratories. The conductor of choice for this R&D program was selected to be Nb_3Sn and therefore LARP became synergetic with another DOE program, the Conductor Development Program (CDP), initiated in 1998 with the goal of improving the performance of Nb3Sn. The LARP, CDP and US Labs HFM activities interacted in an extremely constructive way achieving a substantial increase in the critical current performance of Nb3Sn superconductor and defining the assembly technique for accelerator quality high field Nb3Sn based magnets in different kind of configuration and with different apertures.

The LARP effort was funded at 12-13 M$/year from 2005 with 50% of the funding going directly to magnet development. Several magnets developed by LARP reached and surpassed the design field as shown in Figure 15 right for one of the latest models (HQ02, a 120 mm aperture quadrupole assembled in 2014 and tested at FNAL and CERN). Additionally, LARP has demonstrated the scale-up of the Nb_3Sn technology (i.e. the performance of the technology for magnets as long as 3 m) with the LQ (90 mm aperture Long Quadrupole). The achievements of the US programs, in particular LARP but also of the general R&D high field magnet program, have led to the adoption of the Nb3Sn superconductor solution as the baseline for the HL-LHC new low-β quadrupoles and the 11 T dipoles.

Recently LARP has leveraged the superconducting RF capabilities and resources available at the US Laboratories and Universities to focus on the development of the Crab Cavities achieving transverse fields meeting the technical specifications for this system. In addition, a Wide Band Feedback System is being researched and developed within LARP with the goal of mitigating transverse instabilities in the SPS and, possibly, in the LHC.

DOE and CERN will negotiate the deliverables from the US in the coming years. In the 2016-2017 period, LARP will concentrate on prototyping the elements needed by the HL-LHC project in which the U.S. National Laboratories and Universities have demonstrated excellent capabilities. This prototyping phase is expected to continue until the start of construction in the 2018-2023 period.

3.3. KEK

Within the framework of the CERN-KEK collaboration, KEK has conducted the Nb_3Al superconductor R&D for the high field magnets aimed at the future LHC upgrade from the early 2000s in collaboration with the National Institute of Materials Science (NIMS) in Japan. The Nb_3Al superconductor was considered as one of the promising candidates for the high field accelerator magnet application. Nevertheless, KEK and NIMS faced technical difficulties in the long wire production and in 2011 the Nb_3Al superconductor was unfortunately not ready to start the industrialization for the HL-LHC upgrade, as required by the present schedule.

KEK has officially participated in the FP7 HiLumi LHC design study since 2011 in the context of enhancing the Japanese contribution to the physics outcome from the ATLAS experiment. Following suppression of the R&D on the Nb_3Al superconductor, the main effort was redirected to the conceptual design study of the beam separation dipole magnet, D1, situated immediately after the low-beta insertion quadrupoles in the HL-LHC machine. While the conceptual design study has been dominantly pursued by KEK, the close collaboration with CERN and other partners has strengthened the success of the design study. The D1 magnet is based on the mature Nb-Ti technology. Design challenges are the tight control of the field quality with the large iron saturation, and the accommodation of the heat load and the radiation dose. The research engagement includes the 2-m long model magnet development and its tests at 1.9 K. KEK has also contributed to the HiLumi LHC design study through beam dynamics studies and the cooperative work associated with the crab cavity.

Aside from the HiLumi LHC, KEK has also participated to the LHC Injectors Upgrade (LIU) project. The main collaboration items have been consolidation and upgrade of PS Booster RF systems using Finemet-FT3L technology and development of the longitudinal damper system.

3.4. OTHER COLLABORATIONS

In 2014, CEA (Saclay, FR), INFN (Milano and Genova, IT) and CIEMAT (Madrid, ES), have each signed a further collaboration agreement to carry out design, engineering and prototype work for HL-LHC magnets in addition to the FP7-EC commitment. In all three cases, the CERN funding is about 50%, the rest being at charge of the collaborating institutes. At present a further collaboration with UK Institutes (STFC and six universities federated by Cockcroft Inst.: Lancaster, Manchester, South Hampton, Liverpool, Royal Holloway and Bedford New College, Huddersfield) is being negotiated with CERN (approval of FC of September 2015) to cover critical issues such as the collimation systems, crab cavities, beam diagnostics and beam dynamics and cold powering over the period 2016-2019, with the 50%-50% finance scheme.

Further collaborations are under discussion, namely with Sweden, Greece, Russia and Georgia.

3.4.1. CEA (Saclay)

The CEA agreement concerns "Research and Development for future LHC Superconducting Magnets". It has six technical work packages, covering R&D for HL-LHC and for post-LHC magnets. Among them, the following ones are of HL-LHC interest:

- Design and construction of a single aperture, 1 m long, full coil size model magnet of the first quadrupole of the matching section, Q4. The magnet is based on classical Nb-Ti technology but has very large aperture (90 mm) in a Two-in-One cold mass, and thus presents a number of design challenges.
- Completion of the 13 T, large aperture dipole Fresca2 (a technological Work Package of HL-LHC, that has served as promoter of Nb_3Sn at CERN).
- Studies on Nb_3Sn thermal properties and a finite element model of Nb_3Sn cabling.

3.4.2. INFN (Milano and Genova)

The INFN agreement is also related to R&D on Superconducting Magnets for HL-LHC and concerns two main items:

- Design and construction of a prototype of each of the six high order corrector magnets for the low-β triplet, all with a single aperture of 150 mm. The work is based on Nb-Ti superferric technology and is carried out at INFN-LASA in Milano. An option based on MgB_2 superconductor is also considered as extra effort by INFN.
- Engineering Design of the superconducting recombination dipole magnet, D2, the first Two-in-One magnet, at the end of the common beam pipe. The work is based on Nb-Ti technology, with design challenges coming from the large aperture and the relatively high fields, i.e large magnetic flux, and from the parallel field direction in both apertures, strongly affecting the field quality. The work is performed at INFN-Genova.

3.4.3. CIEMAT (Madrid)

The CIEMAT agreement concerns the design and construction of a 1 m-long prototype of the 150 mm aperture nested orbit corrector dipole for the low-β triplet. It features two dipoles coils, rotated by 90 degrees for simultaneous horizontal and vertical beam steering, in the same aperture. The main challenges are the mechanical structure to withstand the large torque and the unusual force distribution arising when both field directions are needed.

4. GOVERNANCE AND PROJECT STRUCTURE

Given the fact that the application for the FP7 HiLumi LHC Design Study marked the start of the project in its present form, the structure and terminology are borrowed from the typical FP7 style. To avoid any duplication the governance of the whole HL-LHC project is conceived as an extension of the governance that has been instituted for the governance of the FP7-HiLumi LHC.

As noted above, the FP7-HiLumi LHC covers only a few work packages (WPs), although they are the backbone of the upgrade. The WP structure, with task granularity, is the basic structure of the project. LARP is a parallel structure, independently funded, associated to FP7 with connections both at project management level as well as at WP/task level to maximize synergy. KEK is directly member of FP7-HiLumi. It is worth noting that HiLumi LHC is the nickname to indicate the part of HL-LHC that is covered by FP7 funds, even if in practice it has become a popular name to indicate the full project. Figure 14 shows the general governance of the project during the EU funded design study. Each body contains the FP7 part and the part that is not covered by FP7. The Steering Committee is the main managing body: it meets regularly every two months and all WPs are there represented, with the addition of the LARP representatives. It oversees the progress of the technical work and the planning, approving the milestones and deliverables. The Steering Committee usually meets in its “enlarged” form, including also the WPs not covered by FP7 and including the LARP leadership. The Collaboration Board is the highest-level governance body with representation from each institute. The complete description of all bodies is:

- The EC DG Research and Innovation office is the official link of the HL-LHC project to the EU funding agencies.
- The CERN Director General (DG) and Director of Accelerators & Technology represent the link of the HL-LHC project to the CERN management.
- The HL-LHC Collaboration Board is a top-level body for managing the relations with the collaboration partners.
- The CERN Machine Advisory Committee (C-MAC) is an external international scientific advisory board for the CERN accelerator complex and its upgrades. It meets at least once per year and has the function of scientific Advisory Committee for HiLumi LHC as foreseen in its Institution.
- The HL-LHC Project Coordination Office is the main coordination body for the HL-LHC project. It meets weekly and its composition consists of the HL-LHC project leader and his deputy, the HL-LHC Technical Coordinator, the HL-LHC Safety Officer, the HL-LHC Budget officer and the HL-LHC Integration Officer.
- U.S.-LARP and JP-KEK represents the link to the two non-member state collaborators foreseeing major hardware contributions to the HL-LHC project (triplet magnets, crab cavities and new superconducting D1 separation dipole).
- The HL-LHC Coordination Group is a forum for dialog and coordination of goals, parameters & plans for the HL-LHC project, between the CERN management, the LHC experiments, and the LHC Injector Upgrade Project LIU. It is chaired by HL-LHC Project Leader and has representatives from all experiments (spokes persons and technical coordinators), LHC operations, LIU, the CERN Research and A&T Directors and the HL-LHC Technical coordinator.
- The HL-LHC Technical Committee (HL-LHC TC) discusses the technical baseline of the project and drives the generation of Technical Specifications for the individual HL-LHC components, the HL-LHC layout and the integration

aspects. It meets approximately on a bi-weekly rate and features detailed technical discussions.

- The HL-LHC Parameter and Layout Committee (HL-LHC PLC) establishes and maintains a coherent and dynamic list of all HL-LHC parameters and its associated hardware layout. It meets approximately once per month.
- The HL-LHC Steering Committee is a forum for information exchange between all HL-LHC Work Package leaders and the U.S.-LARP representatives. It meets approximately once per month. For the FP7 WP is the body to approve baseline, milestones and deliverable reports and to manage the FP7 collaboration.
- The HL-LHC project features a total of 19 Work Packages, of which 6 are organized under the EU funded HiLumi LHC Design Study. The remaining 13 Work Packages are not part of the EU funded HiLumi Design Study but of the CERN HL-LHC project and 2 of these 13 Work Packages are strictly speaking not required for the HL-LHC project (High Energy LHC and High Field Magnet development) but are naturally related to the other HL-LHC studies.

In case of approval of formal acts for FP7, only the FP7-WP coordinators and FP7 Institutes can vote. It is worth noting that the collaboration is based on a Consortium Agreement, signed by the fifteen members (beneficiaries in FP7 terminology) of FP7-HiLumi LHC. The U.S. laboratories are not members of FP7-HiLumi LHC, however representatives of each U.S. laboratory, included the LARP Director, are co-opted in the enlarged Collaboration Board. The formal link with the U.S. laboratories is assured by the recently signed CERN-DOE Protocol II concerning the LHC and its upgrades. Given the fact that CERN is responsible for the LHC machine, the CERN DG, through his representative in the Collaboration Board, the Project Coordinator, has the right of veto.

The Parameter and Layout Committee and the Technical Committee have mainly technical functions inside the project. The Coordination group, chaired by the HL-LHC leader, constitutes the meeting point between CERN Management, HL-LHC, LIU and Detector Management.

A new structure, more suited to a project that is passing from the design study phase to construction project status, is being implemented as from November 2015, with the end of the FP7 HiLumi LHC Consortium Agreement, as presented in the deliverable report Del-1-11.

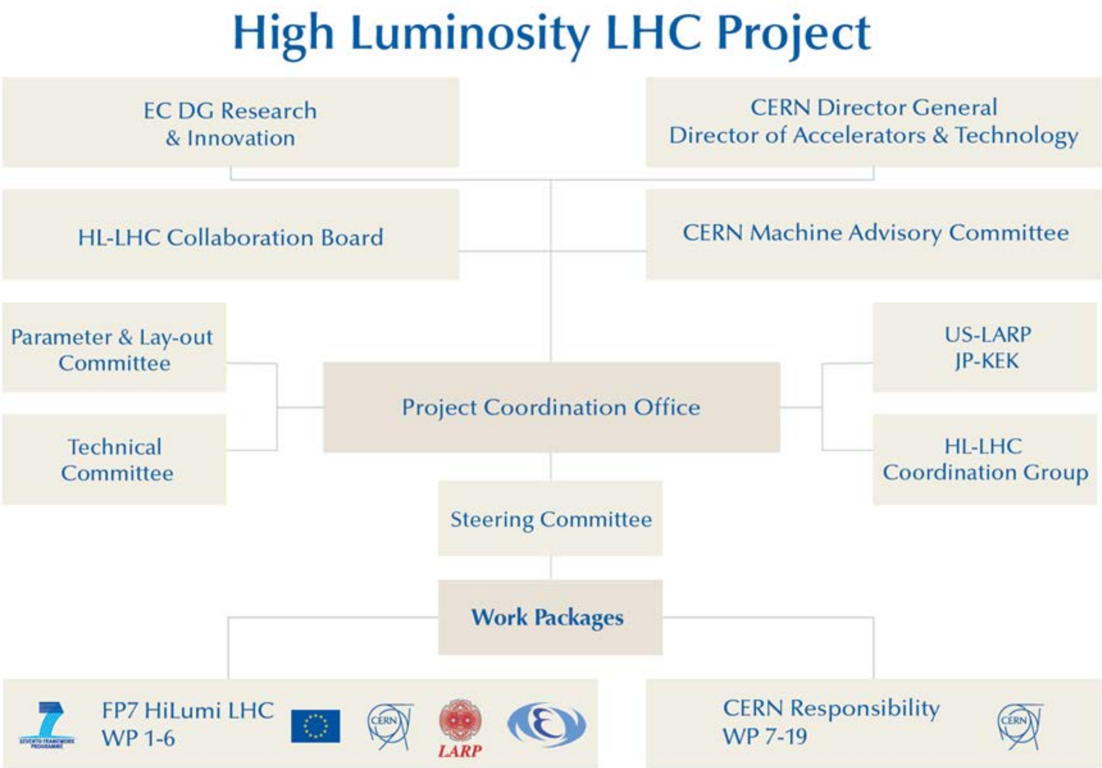

Figure 14. The general governance scheme of FP7-HiLumi LHC, which has been used for the whole HL-LHC project in the founding period 2011-2015 (see text for details).

In Figure 15 the project structure during the EU funded Design Study with all WPs and their coordinators, as well as the main collaborators, is shown. Typically, each WP is structured into 4 to 6 tasks. The tasks are the core of the technical work.

For the post EU funded Design Study the project will be slightly restructured in order to prepare for the hardware prototyping and production phase of the project. A separation of the HL-LHC Technical Committee and the Parameter & Layout Committee was sensible during the design phase when parameters and layout still evolved regularly. However, with the publication of the HL-LHC Technical Design report (TDR) the HL-LHC parameter set and layout should become much more stable while the technical discussions in the HL-LHC TC will focus more on the prototyping and testing of equipment. It seems therefore logical to combine the HL-LHC TC and PLC into one Technical Coordination Committee (TCC) after the HL-LHC design phase and to involve closer the CERN group leaders in the discussions of this new HL-LHC TCC.

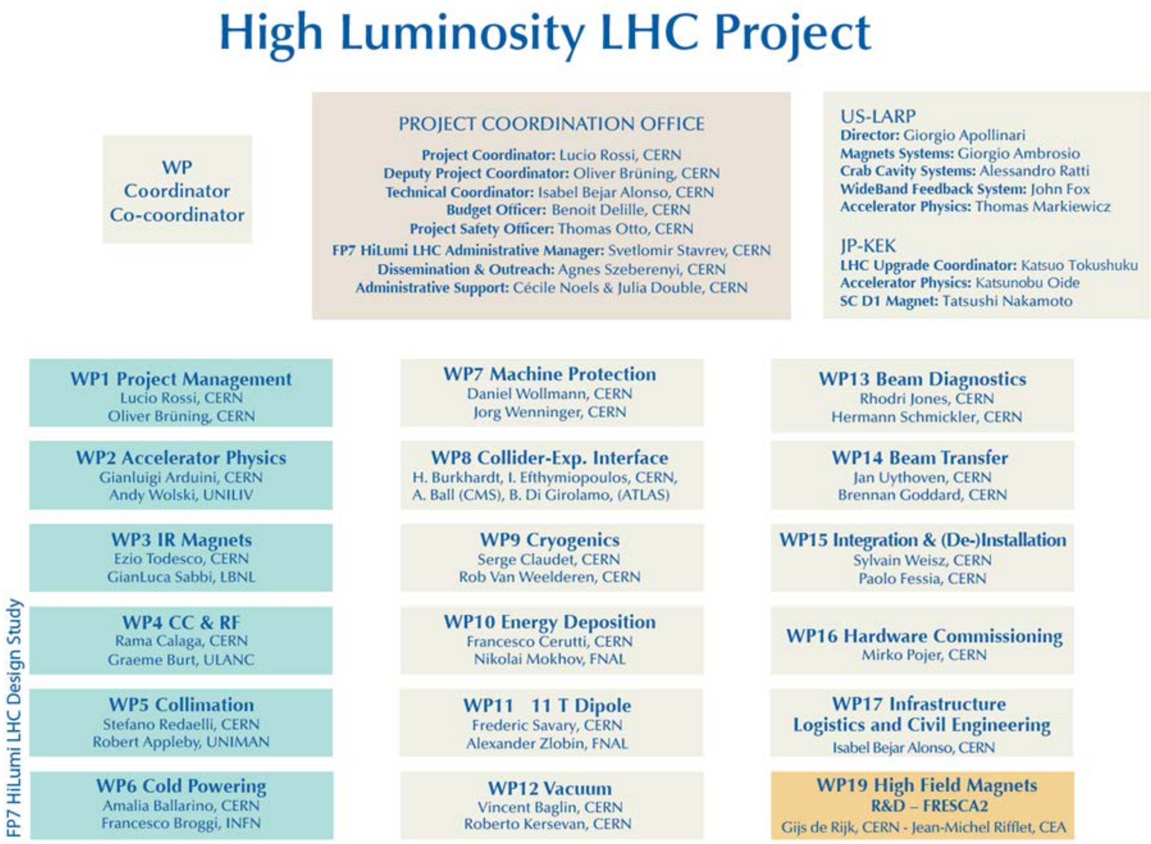

Figure 15. HL-LHC project structure, with FP7 part indicated in dark green. The orange box refers to the High Field Magnets work package, which was started before the HL-LHC in the framework of generic R&D for the LHC upgrade.

The collaborations with the external partners under the EU funded HiLumi Design Study come formally to an end with the end of the EU funding period. However, the HL-LHC project is in the process of developing collaboration agreements with its international partners in order to assure a continued international involvement in the HL-LHC project beyond the EU funded HiLumi Design Study. The most prominent examples for such a continued international contribution are the in-kind US and Japanese production projects for the HL-LHC triplet magnets, crab cavities and new superconducting D1 magnet that evolved out of the JP-KEK and U.S.-LARP R&D collaborations. The preparations of other agreements for hardware deliverables, further R&D studies with hardware deliverables or manpower contributions to the HL-LHC project are on-going (see section 4.4). A continuation of a Collaboration Board or Committee seems therefore well justified and necessary.

The continuation of the CERN Coordination Group (CG) seems likewise necessary as the projects and the experiments require regular and efficient exchange of information between the HL-LHC and LIU projects, the CERN management and the experiments as they enter the implementation phase of their upgrades. The final composition of the new CG will be determined in agreement with the new CERN HL-LHC & LIU Executive Committee.

The continuation of a Steering Committee that assures a smooth exchange of information between the different HL-LHC Work Packages is less obvious. The new HL-LHC TCC will assure the exchange of information between the different work packages and regular extended meetings of the HL-LHC Project Office can look after other outstanding issues.

A new Executive Committee under the chairmanship of the CERN director of accelerators will furthermore look after urgent actions and decisions that will affect both the HL-LHC and the LHC Injector Upgrade (LIU) projects. Figure 16 summarizes the above considerations for the HL-LHC Project governance after the end of the EU funded HiLumi Design Study. The IEFC and LMC boxes refer to the committees CERN looking after the operational aspects of the injector and experimental area complex and the LHC respectively.

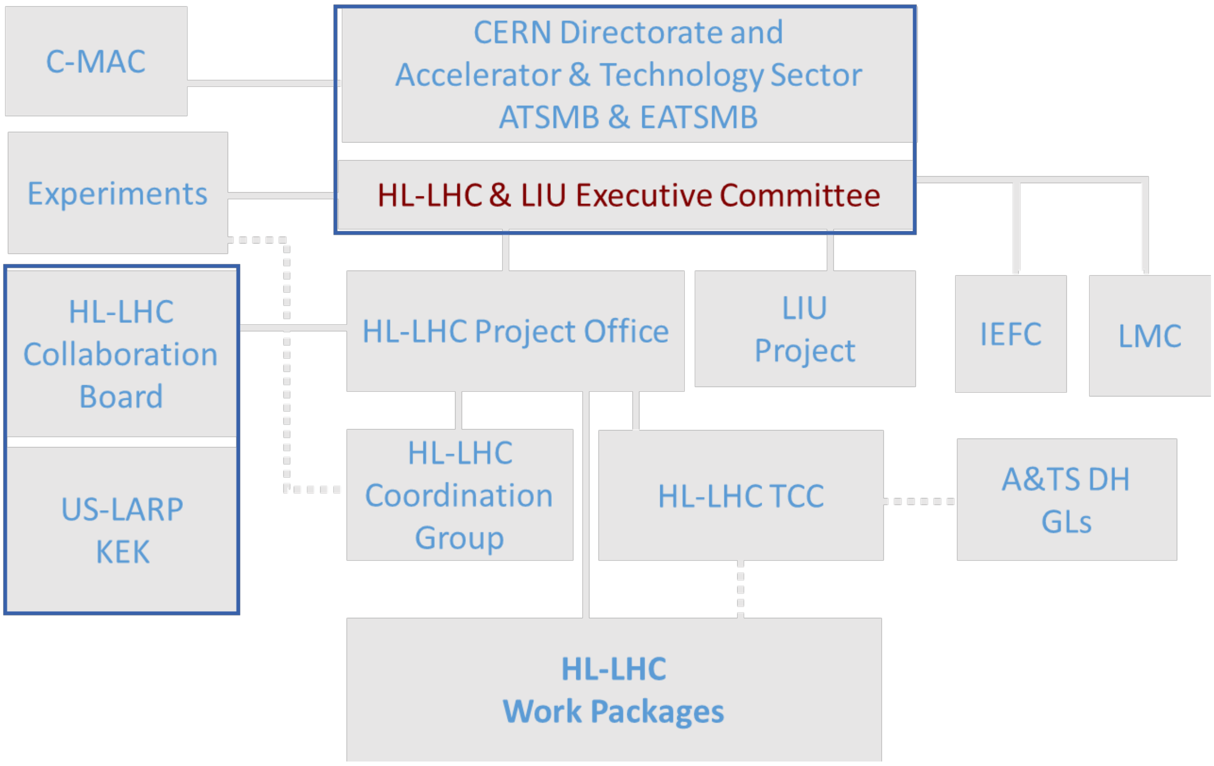

Figure 16. The HL-LHC project new governance after the end of the EU funded HiLumi Design Study.

5. TECHNICAL DESIGN REPORT – FULL TEXT

Due to space limitations, the full text of the TDR is publicly available from CDS: https://edms.cern.ch/ui/file/1558149/1.0/HL_TDR.2015.11.06.V02.pdf

6. FUTURE PLANS / CONCLUSION / RELATION TO HL-LHC WORK

The technical design report is the main legacy of the FP7-HiLumi LHC Design Study. A comprehensive four hundred pages document testifies the quality and completeness of the work. It has been the base of the final approval by CERN COUNCIL of September 2015, when the full budget for the HL-LHC has been approved.

Now, the HL-LHC project is heading toward a phase of prototyping and industrialization, to be followed soon by construction, supported by a vast International Collaboration.

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