Chapter 1

Introduction to the HL-LHC Project[*]

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The Large Hadron Collider (LHC) is one of largest scientific instruments ever built. It has been exploring the new energy frontier since 2010, gathering a global user community of 7,000 scientists. To extend its discovery potential, the LHC will need a major upgrade in the 2020s to increase its luminosity (rate of collisions) by a factor of five beyond its design value and the integrated luminosity by a factor of ten. As a highly complex and optimized machine, such an upgrade of the LHC must be carefully studied and requires about ten years to implement. The novel machine configuration, called High Luminosity LHC (HL-LHC), will rely on a number of key innovative technologies, representing exceptional technological challenges, such as cutting-edge 11–12 tesla superconducting magnets, very compact superconducting cavities for beam rotation with ultra-precise phase control, new technology for beam collimation and 300-meter-long high-power superconducting links with negligible energy dissipation.

HL-LHC federates efforts and R&D of a large community in Europe, in the US and in Japan, which will facilitate the implementation of the construction phase as a global project.

1. Context and Objectives

The Large Hadron Collider (LHC) was successfully commissioned in March 2010 for proton–proton collisions with a 7 TeV center-of-mass energy and has delivered 8 TeV center-of-mass proton collisions since April 2012. The LHC is pushing the limits of human knowledge, enabling physicists to go beyond the Standard Model: the enigmatic Higgs boson, mysterious dark matter and the world of supersymmetry are just three of the long-awaited mysteries that the LHC might unveil. The announcement given by CERN on 4 July 2012 about the discovery of new

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boson at about 125 GeV, the long awaited Higgs particle, is hopefully the first fundamental discovery of a series that LHC can deliver. Thanks to the LHC, Europe has decisively regained world leadership in High Energy Physics, a key sector of knowledge and technology. The LHC can act as catalyst for a global effort unrivalled by other branches 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 baseline programme till 2025 is schematically shown in Fig. 1. After entering in the near-to-nominal energy regime of 13 TeV center-of-mass energy in 2015, (hoping to reach the 14 TeV in the subsequent year) it is expected that the LHC will reach the design peak **luminosity**[1] of 10^{34} cm^{-2}s^{-1} and a total integrated luminosity over a one year of about 40 fb^{-1}. Then in the period 2015–2022 LHC will hopefully increase the peak luminosity: indeed margins have been taken in the design to allow, in principle, to reach about two times the nominal design performance. The baseline programme for the next ten years is depicted in Fig. 1, while Fig. 2 shows the graphs of the possible evolution of peak and integrated luminosity.

After 2020 the statistical gain in running the accelerator without an additional considerable luminosity increase beyond its design value will become marginal. The running time necessary to half the statistical error in the measurements will be more than ten years after 2020. Therefore to maintain scientific progress and to explore its full capacity, the LHC will need to have a decisive increase of its luminosity. That 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 ESFRI Roadmap of 2006 and its 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], 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.*"

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[1] **Luminosity** is the number of collisions per square centimeter and per second, cm^{-2}s^{-1}.

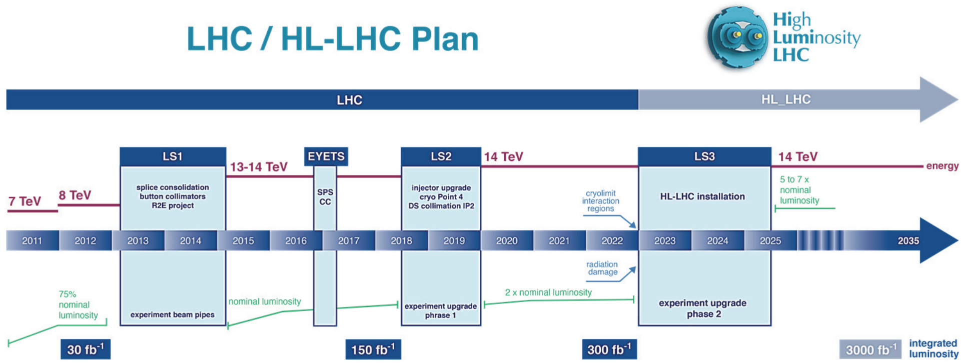


Fig. 1. LHC baseline plan for the next decade and beyond. In terms of energy of the collisions (upper line) and of luminosity (lower lines). The first long shutdown (LS1) 2013–14 is to allow design parameters of beam energy and luminosity. The second one, LS2 in 2018–19, is for securing luminosity and reliability as well as to upgrade the LHC Injectors. After LS3, in 2025 the machine should have the High Luminosity configuration (HL-LHC).

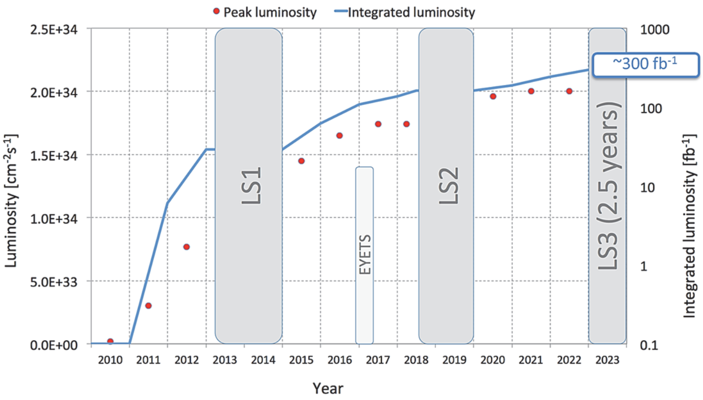


Fig. 2. Possible peak luminosity evolution (till the so-called “ultimate” limit) with consequent best forecast for integrated luminosity for the first decade of operation of LHC. Superimposed are the three long shutdowns (LS1, LS2, LS3) and the Extended Year End Technical Stop, as proposed in RLIUP and approved by CERN management and endorsed by CERN Council of December 2013. Also indicated the integrated luminosity goal of the LHC baseline program: 300 fb^{-1}.

The importance of the LHC upgrade in luminosity for the future of High Energy Physics has been also recently re-affirmed by the May 2014 resolution of the so-called P5 panel in the USA [4], a critical step in updating the USA strategy for HEP, with the following wording: “*Recommendation 10: … The LHC upgrades constitute our highest-priority near-term large project.*”

In this context, CERN has put in place, at the end of 2010, the High Luminosity LHC (HL-LHC) project [5, 6]. Started as a Design Study, HL-LHC has become CERN’s major construction project for the next decade 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 the June 2014.

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

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

The time horizon foresees the installation of the main hardware for HL-LHC during LS3 and commissioning the new machine configuration in the period 2023–2025.

All hadron colliders in the world have so far produced a total combined integrated luminosity of about 10 fb^{-1}; LHC has delivered nearly 30 fb^{-1} at the end of 2012 and should reach 300 fb^{-1} in its first 10–12 years of life. The High Luminosity LHC is a major and extremely challenging upgrade. For its successful realization, a number of key novel technologies have to be developed, validated and integrated. The work is initiated with the FP7 Design Study HiLumi LHC which, approved by EC in the Seventh Framework Programme (FP7-INFRA) in 2011 with the highest mark [7], is instrumental in initiating a new global collaboration for the LHC that matches the spirit of the worldwide user community of the LHC experiments.

The High Luminosity LHC project is working in close connection with the companion ATLAS and CMS upgrade projects of 2018–2023 and the upgrade foreseen in 2018 for both LHCb and Alice, as discussed in [8]. Furthermore, the performance of the high luminosity machine will depend on the performance of the injector chain, which is also being upgraded by a companion program, the LHC Injector Upgrade (LIU) program [9].

2. Approach for the Upgrade

The (instantaneous) luminosity L can be expressed as:

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

where:

γ is the proton beam energy in unit of rest mass;
n_b is the number of bunches in the machine: 1380 for 50 ns spacing and 2808 for 25 ns;

N is the bunch population. $N_{\text{nominal 25 ns}}$: 1.15×10^{11} p ($\Rightarrow$ 0.58 A of beam current at 2808 bunches);
f_{rev} is the revolution frequency (11.2 kHz);
β^* is the beam beta function (focal length) 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 0.55 m of β^*, 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. size, respectively (16.7 μm and 7.55 cm).

2.1. *Present luminosity limitations and hardware constraints*

There are various expected limitations to a continuous increase in luminosity, either in beam characteristics (injector chain, beam impedance and beam-beam interactions in the LHC) or in technical systems. Mitigation of potential performance limitations arising from the LHC injector complex are addressed by the LIU project, which should be completed in 2019 (LS2). Any potential limitations coming from the LHC injector complex put aside, it is expected that the LHC will reach a performance limitation from the beam current, from cleaning efficiency at 350 MJ beam stored energy and from the acceptable pile-up level. The ultimate value of bunch population with nominal LHC beam parameters should enable to reach $L = 2\times10^{34}$ cm^{-2}s^{-1}. Any further performance increase of the LHC will require significant hardware and beam parameter modifications with respect to the designed LHC configurations.

Before discussing the new configuration, it is useful to recall the systems that need to be changed, and possibly improved, just because they become more vulnerable to breakdown and accelerated wear out. This goes well beyond the on-going basic consolidation.

(1) *Inner Triplet Magnets*: At about 300 fb^{-1} some components of the low-beta triplet quadrupoles and their corrector magnets, we will have received a dose of 30 MGy, entering in the region of radiation damage. The quadrupoles may withstand 400–700 fb^{-1} but some corrector magnets of nested type are likely to wear out are already above 300 fb^{-1}. Damage must be anticipated because the most likely way of failing is through sudden electric breakdown, entailing serious and long repairs. That is why replacement of the triplet must be envisaged before damage. Replacement of the low-beta triplet is a long intervention, requiring one to two years shutdown and must be coupled with a major detector upgrade.

(2) *Cryogenics*: To increase flexibility of intervention and then availability (i.e. integrated luminosity) we plan to install a new cryo-plant in P4 for a full

separation between SCRF and Magnets cooling. In the long term, the cooling of the inner triplets and matching section magnets must be separate from the magnets of arc, to avoid that an intervention in the triplet region requires warm up of the entire arc (an operation of three months, not without risk).

(3) *Collimation*: The collimation system has been designed for the first phase of LHC life, but will certainly need a renovation plan mainly concerning the momentum and betatron cleaning in P3 and P7, as well as the tertiary collimators protecting the triplets. Any small gain in triplet aperture and performance must be accompanied by an adequate consolidation or modification of the collimation system. A second area that will require a special attention to the collimation system is the Dispersion Suppressor (DS), where a leakage of off-momentum particle into the first and second main superconducting dipole, has been already identified as a possible LHC performance limitation. The most promising concept is to substitute an LHC main dipole with a dipole of equal bending strength (121 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 placing special collimators. A further improvement of the collimation system will be the use of new material for the jaws, in order to reduce the impedance (half of the LHC impedance is attribute to collimators). A molybdenum-graphite composite, coated with molybdenum, seems the best solution, capable to reduce the impedance of factor five to ten, keeping the robustness of the present design.

(4) *R2E and SC links for remote cold powering*: A considerable effort is under way to study how to replace the radiation sensible electronic boards with rad-hard cards. A complementary solution is also pursued for special zones: removal of the power supplies and associated DFBs (electrical feed-boxes, delicate equipment today in line with the continuous cryostat) out of the tunnel, possibly on the surface. LHC availability will be improved. In particular for Point 7 where a set of 600 A power converters are placed in front of the betatron cleaning collimators, removal will be done in a lateral tunnel since here ground surface is not accessible. Displacement of power converter to far away distance or surface is possible only thanks to a novel technology, not yet developed at the LHC design and construction: Superconducting links (SCLs) made out of HTS (YBCO or Bi-2223) or MgB_2 superconductors.

(5) *QPS, machine protection and remote manipulation*: Other systems will become a bottleneck along with aging of the machine and higher performance of 40 to 60 fb^{-1} per year:

    (a) *Quench Protection System* (QPS) of the superconducting magnets, which is based on a design of almost twenty years ago.

(b) *Machine protection*: improving vulnerability to mis-injected beams, to kickers sparks and asynchronous dumps. The kicker system is, with collimation and TDI, the main barrier against severe beam induced damage. Not only the kicker system, but also the interlock system needs renovation after 2020.

(c) *Remote manipulation*: the level of activation from 2020, and even earlier, requires a carefully study and development of special equipment to allow replacing collimators, magnets, vacuum components, etc., according to ALARA principle. While full robotics is difficult to implement, given the real conditions, remote manipulation, enhanced reality and supervision is the key to minimize the radiation dose to operators.

2.2. *Upgraded systems for the high luminosity*

2.2.1. *Luminosity leveling and availability*

Both 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 leveling. As shown in Fig. 3 (left), the luminosity profile without leveling quickly decreases from the initial peak value, due to "proton burning" (protons consumed in collisions). By designing the collider to operate with a constant luminosity, i.e. "leveling" it and suppressing its decay for a good part of the fill, the average luminosity is almost the same as the one of a run without leveling, see Fig. 3 (right), however with the advantage that the maximum peak luminosity is smaller.

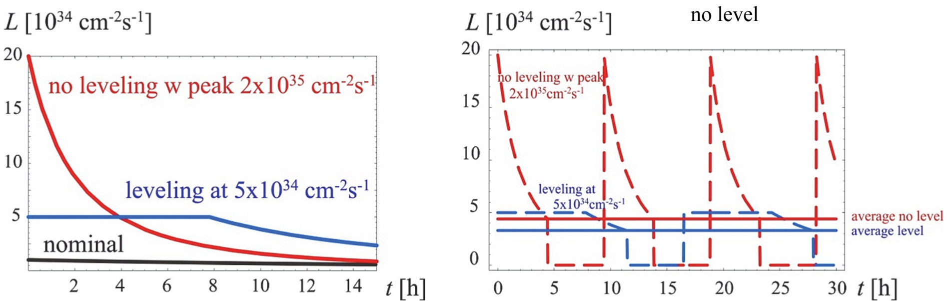


Fig. 3. Left: Luminosity profile for a single long run starting at nominal peak luminosity (black line), with upgrade no leveling (red line) with leveling (dotted line). Right: Luminosity profile with optimized run time, without and with leveling (blue and red dashed lines), and average luminosity in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

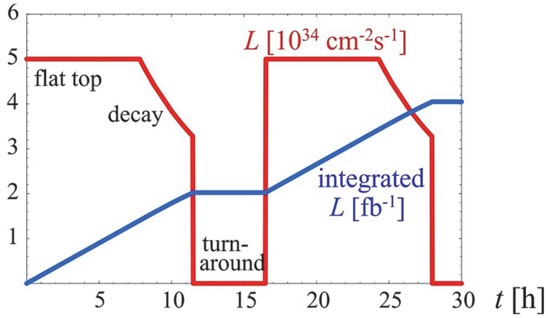


Fig. 4. Luminosity cycle for HL-LHC with leveling and a short decay (optimized for integrated luminosity). The set of parameters generating cycle are the 25 ns column of Table 1, standard.

The fact that the maximum leveled luminosity is limited, means that to maximize the integrated value one needs to maximize the run length, which can be obtained by filling the maximum number of protons, i.e. by maximizing the beam current: $I_{beam} = n_b \times N$. Other key factors for maximizing the integrated luminosity and obtaining the challenging goal of 3 fb^{-1}/day, see Fig. 4, are a short average machine turnaround time and a good overall machine "efficiency" defined as the ratio between actual time spent in physics production and the physics time of the ideal cycle. Clearly, for maximizing the integrated luminosity the efficiency counts almost as much as the virtual peak performance.

HL-LHC with 150 days of physics needs an efficiency of ca. 40%. During the 2011 run the efficiency varied, without luminosity leveling and the added system complexity of the HL-LHC (e.g. Crab Cavity operation), between 20% and 40%. Requiring an efficiency much higher than the one of the present LHC, with a (leveled) luminosity five times the nominal one and additional technically challenging hardware, 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.

2.2.2. *Upgrade parameters*

Table 1 lists the main parameters foreseen for the high luminosity operation. Although the 25 ns bunch spacing remains the baseline, given the experience of the first years of operation, 50 ns is kept as a viable alternative, in case the e-cloud or other unforeseen effects undermine the 25 ns performance. For similar reasons, a slightly different parameter set with very small emittance beams (BCMS) is also maintained in case the LHC operation at with high beam intensities reveals unexpected sources for emittance blow-up during the beam injection and acceleration.

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

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

[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 3 μs 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 emitance in collision for 25 ns/50 ns 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 50 ns beam in the injectors rather than two main bunches, hence the number of collisions is given as zero.

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

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

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

An upgrade should provide the possibility of performance increase over a wide range of parameters, such that the machine experience and experiments can eventually find the practical best 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 cavity, Collimation, Cryogenics, Kickers, Vacuum, beam diagnostics, QPS, various controllers, etc. Radiation effects put aside, all systems have been designed in principle for $I_{beam} = 0.86\ \mathrm{A}$, the so-called "ultimate" beam current. However this is still to be experimentally proven and for the goal of HL-LHC we need to go beyond the ultimate value by 30% with 25 ns bunch spacing.

For HL-LHC it is needed to increase the beam brightness, which is a property that must be maximized at beginning of the beam generation and then preserved throughout the entire injector chain and LHC itself, i.e. it is a global property. The LIU project has as primary objective to increase the brightness at the LHC injection, basically increasing the number of protons per bunch by a factor two above what we have today while keeping the emittance at the present low value.

β^* and canceling the reduction factor R: A classical route to the luminosity upgrade is to reduce β^*, the optical function at the Interaction Points (IPs), by means of stronger and larger aperture low-β triplet quadrupoles. However a reduction in β^* value implies an increase of beam sizes inside the low-β triplet quadrupoles and a wider crossing angle, which both require in turn larger aperture low-β triplet quadrupole magnets, a larger D1 (first separation/recombination dipole) and a few modifications in the matching section, too. Stronger chromatic aberrations coming from the larger β-functions inside the triplet magnets may exceed the strength of the existing correction circuits. The peak beta-function inside the triplet magnets is also limited by the possibility to match the optics to the regular beta functions of the neighboring arcs. A previous study has shown that a practical limit in LHC is $\beta^* = 30\text{–}40$ cm, compared to the 55 cm foreseen in nominal operation. However a novel scheme called Achromatic Telescopic Squeeze (ATS) uses the adjacent arcs as enhanced matching sections and the increase of the beta-functions in those arcs to boost at constant strength the efficiency of the lattice sextupoles. 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 is enabled. For the β^* reduction the quadrupole magnets need to double the aperture, with a peak field 50% above the present LHC, requiring a new more advanced superconducting technology based on Nb_3Sn.

The drawback of very small β^* is that it requires larger crossing angle, which entails a reduction of the geometrical luminosity reduction factor 'R', see luminosity expression. In Fig. 5 the reduction factor is plotted for a constant normalized beam separation of 10σ vs. β^* values.

An efficient and elegant solution for compensating the geometric reduction factor is the use of special superconducting RF crab cavities, capable to generate transverse electric field to rotate each bunch by $\theta_c/2$, such as they collide effectively head on, overlapping perfectly at the collision point, see Fig. 6. Crab cavities make then accessible the full performance reach of the small β^* that the ATS scheme and the large low-beta triplet quadrupoles can generate: their primary function is boosting the virtual peak luminosity for attaining the full HL-LHC performance.

The lay-out and main hardware modifications required to meet the parameters listed in Table 1 are described in Chapter 3 of this book (The High Luminosity LHC Machine).

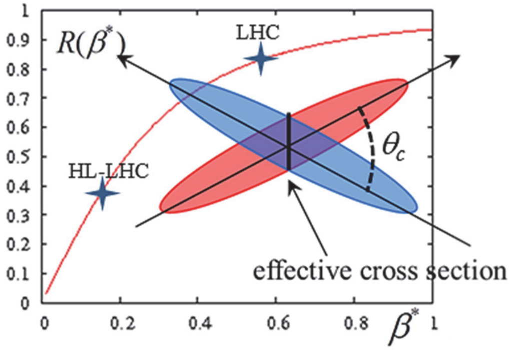


Fig. 5. Behavior of geometrical reduction factor of luminosity vs. β^* for constant normalized beam separation with indicated two operating points: Nominal LHC and HL-LHC. The sketch of bunch crossing shows the reduction mechanism.

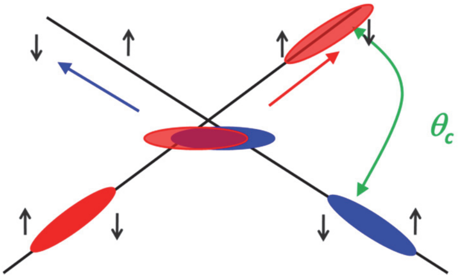


Fig. 6. Effect of the crab cavity on the beam (small arrows indicate the torque on the beam by transverse varying RF field).

2.3. *Project: performance, plan and cost*

The performance of the HL-LHC, both in terms of peak and integrated luminosity, is reported in the plot of Fig. 7.

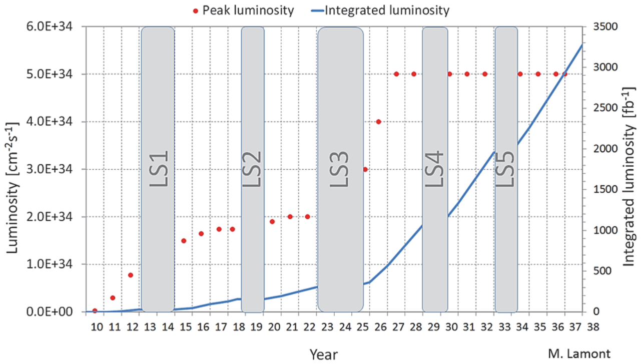


Fig. 7. Peak luminosity (red dots) and integrated luminosity (blue line) vs time till 2035.

The plan is based on the following milestones:

2014: Preliminary Design Report (PDR)
2015: End of Design Phase, issue of the Technical Design Report (TDR)
2016: Proof on test bench of main hardware
2017: Test prototypes (including Crab Cavity test in SPS) and issue of TDR_v2
2017–2021: Construction and test of long lead hardware (Magnets, Crab Cavities, SC links, collimators)
2018–2019: LS2 – Installation of Cryo-plant P4, DS collimators (11T) in P2, SC link in P7
2021–2022: String test of Inner triplet
2023–2025: LS3 – Main installation and commissioning

The Cost-to-Completion of the full HL-LHC project, according to the initial evaluation of 2011, amounts to about 830 MCHF for Material (CERN accounting) and requires between 1000 and 1500 FTE-y.

In June 2014, CERN draft budget accounts for about 750 MCHF for the HL-LHC project till 2025, with certain guess of in-kind contributions both from the USA and Japan. The discrepancy is not critical at this stage, since modifications of certain equipment is not yet fully defined. LHC operation at full energy and intensity will give important indications, as well as the thorough investigation of the connection with LHC consolidation project and the various studies to make savings without compromising performance. Of course, additional in-kind contributions to the hardware baseline would be equivalent to a budget increase.

A further possibility is to stage the project by using also LS4, see Fig. 7. Indeed the performance "forecast" of Fig. 7 is somehow theoretical: there will certainly be a learning curve to pass from a luminosity of 2×10^{34} cm^{-2}s^{-1} to (leveled) 5×10^{34} cm^{-2}s^{-1}, favoring staging. However, only when installation of all equipment is completed, the 250 fb^{-1} annual integrated luminosity goal can be attained and, possibly, overcome.

2.4. *The international collaboration*

The LHC luminosity upgrade was born even more international than LHC, since USA laboratories started to work on it, with considerable resources, well before CERN. In 2002–2003 common work between US labs and CERN indicated the route for upgrade [10]. Right after the LARP (LHC Accelerator Research Program) was set up and approved by DOE [11] and become a ten-year program with a financing from 2008 of about 12 M$/year (in USA accounting). LARP heavily profited for the low-β triplet quadrupoles R&D of the DOE-Conductor Development Program, launched in 1998, which was instrumental for improving Nb_3SN to accelerator quality [12]. Meanwhile CERN was heavily engaged in the LHC construction and commissioning and could only participated to an EC-FP6 program in 2004–2008, called CARE that contained a modest program for the LHC upgrade. Then two EC-FP7 programmes helped to reinforce the Design and R&D for the LHC upgrade in Europe, although a modest level: SLHC-PP and EuCARD. KEK in Japan, in the framework of the permanent CERN-KEK collaboration, engaged in small activities for the LHC upgrade from 2008. LARP provided, until 2011, the largest part of the work for the LHC upgrade.

Finally with the approval of the EC-FP7 Design Study HiLumi LHC in 2011, and the maturing of all conditions illustrated in Section 1, the collaboration for HL-LHC took the present form. It is worth noticing that FP7 HiLumi Design Study covers only the design of a few components of the general lay-out, given the limited amount of funding in the program. However, it has allowed to form and structure a European participation to the upgrade at the very beginning of the project, something that was missing at the time of LHC. Since 2014, CEA (Saclay, FR), INFN (Milano and Genova, IT) and CIEMAT (Madrid, ES), have signed each a further collaboration agreement to carry out design, engineering and prototypal works for HL-LHC magnets in addition to the FP7-EC commitment. In all three cases the CERN funding is about 50%, the rest coming at charge of the collaborating Institutes. Figure 8 illustrates the various collaboration branches.

As stated above, the FP7-HiLumi LHC covers only a few WPs, which are the backbone of the upgrade. Work Packages are the basic structure of all FP7 projects: the WP structure, with task branching, is now the basic structure of the project.

LARP is a parallel structure, independently funded, but associated to FP7 with connections both at project management level as well as at WP/task level, to assure a maximum synergy. KEK is directly member of FP7-HiLumi. It is worth noticing that HiLumi LHC is the nickname to indicate the part of HL-LHC that is covered by FP7 funds, even if in practice has become a popular name to indicate the full project. Figure 9 shows the general governance of the project, while Fig. 10 illustrates the detailed structure in WP. Typically, each WPs is composed by 3 to 6 tasks.

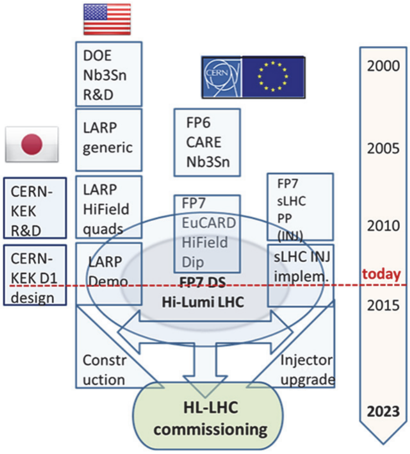


Fig. 8. The International Collaboration and various paths toward the High Luminosity LHC.

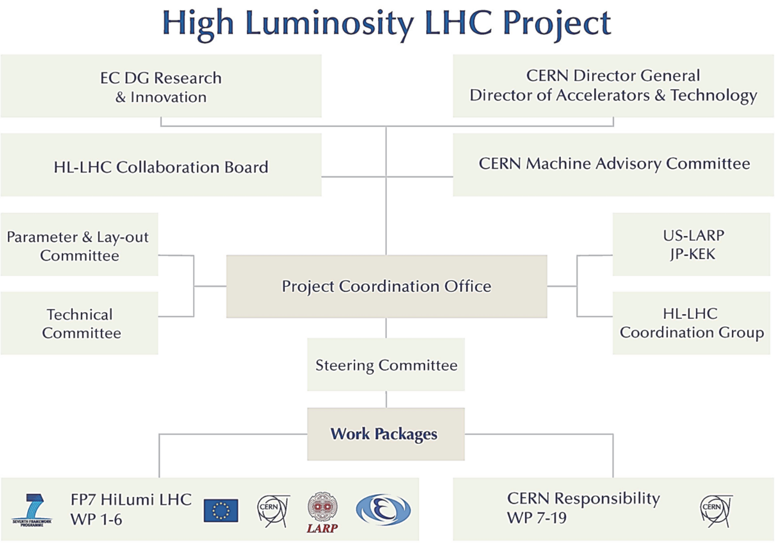
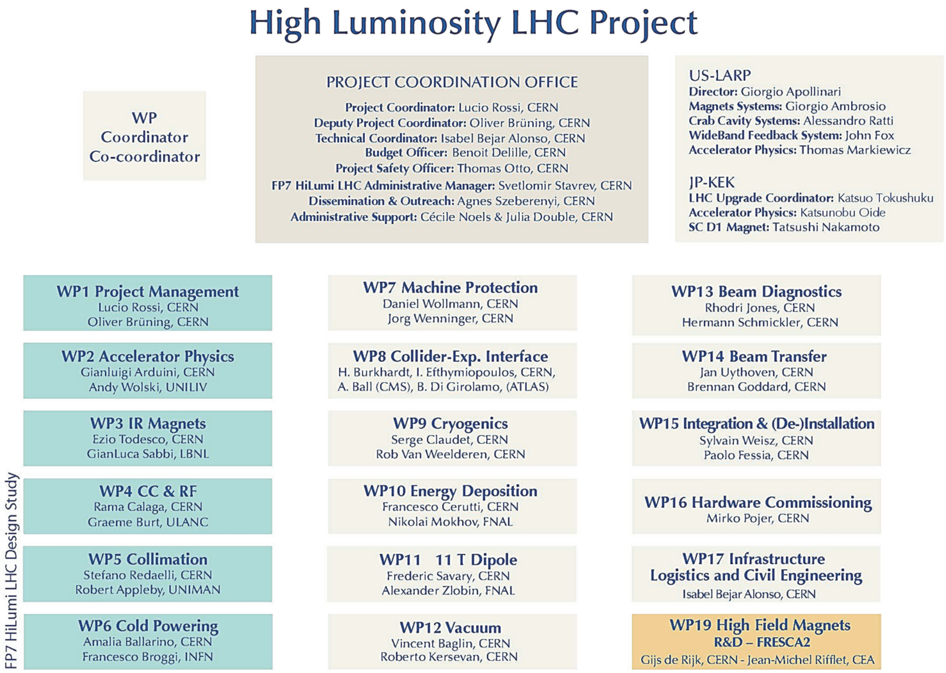


Fig. 9. Project structure and governance.



High Luminosity LHC Project

WP
Coordinator
Co-coordinator

PROJECT COORDINATION OFFICE
Project Coordinator: Lucio Rossi, CERN
Deputy Project Coordinator: Oliver Brüning, CERN
Technical Coordinator: Isabel Bejar Alonso, CERN
Budget Officer: Benoit Delille, CERN
Project Safety Officer: Thomas Otto, CERN
FP7 HiLumi LHC Administrative Manager: Svetlomir Stavrev, CERN
Dissemination & Outreach: Agnes Szeberenyi, CERN
Administrative Support: Cécile Noels & Julia Double, CERN

US-LARP
Director: Giorgio Apollinari
Magnets Systems: Giorgio Ambrosio
Crab Cavity Systems: Alessandro Ratti
WideBand Feedback System: John Fox
Accelerator Physics: Thomas Markiewicz

JP-KEK
LHC Upgrade Coordinator: Katsuo Tokushuku
Accelerator Physics: Katsunobu Oide
SC D1 Magnet: Tatsushi Nakamoto

FP7 HiLumi LHC Design Study

WP1 Project Management
Lucio Rossi, CERN
Oliver Brüning, CERN

WP2 Accelerator Physics
Gianluigi Arduini, CERN
Andy Wolski, UNILIV

WP3 IR Magnets
Ezio Todesco, CERN
GianLuca Sabbi, LBNL

WP4 CC & RF
Rama Calaga, CERN
Graeme Burt, ULANC

WP5 Collimation
Stefano Redaelli, CERN
Robert Appleby, UNIMAN

WP6 Cold Powering
Amalia Ballarino, CERN
Francesco Broggi, INFN

WP7 Machine Protection
Daniel Wollmann, CERN
Jorg Wenninger, CERN

WP8 Collider-Exp. Interface
H. Burkhardt, I. Efthymiopoulos, CERN,
A. Ball (CMS), B. Di Girolamo, (ATLAS)

WP9 Cryogenics
Serge Claudet, CERN
Rob Van Weelderen, CERN

WP10 Energy Deposition
Francesco Cerutti, CERN
Nikolai Mokhov, FNAL

WP11 11 T Dipole
Frederic Savary, CERN
Alexander Zlobin, FNAL

WP12 Vacuum
Vincent Baglin, CERN
Roberto Kersevan, CERN

WP13 Beam Diagnostics
Rhodri Jones, CERN
Hermann Schmickler, CERN

WP14 Beam Transfer
Jan Uythoven, CERN
Brennan Goddard, CERN

WP15 Integration & (De-)Installation
Sylvain Weisz, CERN
Paolo Fessia, CERN

WP16 Hardware Commissioning
Mirko Pojer, CERN

WP17 Infrastructure Logistics and Civil Engineering
Isabel Bejar Alonso, CERN

WP19 High Field Magnets
R&D – FRESCA2
Gijs de Rijk, CERN - Jean-Michel Rifflet, CEA

Fig. 10. Simplified project governance and project work structure at July 2014. In dark green are evidenced the work packages which are co-financed by the European Commission under FP7. WP19 has a different color because it started as technological R&D program before the setting up of HL-LHC. The organigram reflect the status of summer 2014.

Table 2. List of the Institutes that are members of the FP7-HiLumi LHC Consortium.

Short Name	Country	Logo
CERN	Geneva Switzerland	CERN
CEA	Saclay France	cea
DESY	Hamburg Germany	DESY
INFN	Frascati Italy	INFN
CSIC	Madrid Spain	CSIC Consejo Superior de Investigaciones Científicas
EPFL	Lausanne Switzerland	EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
SOTON	Southampton United Kingdom	UNIVERSITY OF Southampton
RHUL	London United Kingdom	Royal Holloway University of London
STFC*	Daresbury United Kingdom	Science & Technology Facilities Council
ULANC*	Lancaster United Kingdom	LANCASTER UNIVERSITY
UNILIV*	Liverpool United Kingdom	UNIVERSITY OF LIVERPOOL
UNIMAN*	Manchester United Kingdom	MANCHESTER 1824 The University of Manchester
HUD	Huddersfield United Kingdom	University of HUDDERSFIELD
KEK	Tsukuba Japan	KEK-JAPAN
BINP	Novosibirsk Russia	

*Members of Cockcroft Institute

Table 3. List of the USA Institutions collaborating with the High Luminosity LHC Project.

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

The mechanism of FP7 funding is such that each of the thirteen European Institutions that are members of HiLumi LHC have to match the EC contribution with their internal funding: in case of HiLumi the matching funds equal the EC funds (except for CERN that receives from the EU only 17% of the total CERN cost for the design study, mainly for the management and coordination). Table 2 lists the 15 FP7-HiLumi Institutions and Table 3 the four USA-LARP institutions.

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