High Luminosity LHC

Project Description

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Abstract

The High Luminosity LHC (HL-LHC) is a novel configuration of the Large Hadron Collider, aiming at increasing the luminosity by a factor five or more above the nominal LHC design, to allow increasing the integrated luminosity, in the high luminosity experiments ATLAS and CMS, from the 300 fb$^{-1}$ of the LHC original design up to 3000 fb$^{-1}$ or more. This paper contains a short description of the main machine parameters and of the main equipment that need to be developed and installed. The preliminary cost evaluation and the time plan are presented, too. Finally, the international collaboration that is supporting the project, the governance and the project structure are discussed, too.

The project is partially supported by the EC as FP7 HiLumi LHC Design Study under Grant no. 284404. In addition to the FP7-Hilumi LHC consortium, the Project relies on the special contributions by: USA (LARP), Japan (KEK), France (CEA), Italy (INFN-Milano and Genova), Spain (CIEMAT).

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High Luminosity Large Hadron Collider: HL-LHC

1 Introduction

The Large Hadron Collider (LHC) was successfully commissioned in 2010 for proton-proton collisions with a 7 TeV centre-of-mass energy and delivered 8 TeV centre-of-mass proton collisions from April 2012 to the end of 2013. The LHC is pushing the limits of human knowledge, enabling physicists to go beyond the Standard Model. The announcement given by CERN on 4 July 2012 about the discovery of a new boson at about 125 GeV, the long awaited Higgs particle, is the first fundamental discovery, hopefully the first of a series that LHC can deliver.

It is a remarkable era for cosmology, astrophysics and high energy physics and the LHC is at the forefront of attempts to understand the fundamental nature of the universe. The discovery of the Higgs boson in 2012 is undoubtedly a major milestone in the history of physics. Beyond this, the LHC has the potential to go on and help answer some of the key questions of the age: the existence, or not, of supersymmetry; the nature of dark matter; the existence of extra dimensions. It is also important to continue to study the properties of the Higgs in more detail – here the HL-LHC is well placed for making a significant contribution.

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 design value. The integrated luminosity goal is a factor ten times the nominal design value. As a highly complex and optimized machine, such an upgrade must be carefully studied. The necessary developments will require 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 long 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,Sn) 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 HL-LHC in a Nutshell

The LHC baseline programme until 2025 is shown schematically in Figure 1. After entering into the nominal energy regime of 13-14 TeV centre-of-mass energy in 2015, it is expected that the LHC will
reach the design luminosity of $1 \times 10^{34}$ 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 upgrade 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 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 will allow design parameters of beam energy and luminosity to be reached. The second long shutdown (LS2) in 2018-19, will consolidate luminosity and reliability as well as upgrade the LHC Injectors. After LS3, 2023-2025, the machine will be in the High Luminosity configuration (HL-LHC).](image)

After 2020 the statistical gain in running the accelerator without a significant luminosity increase beyond its design value will become marginal. The running time necessary to halve 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. 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.” Following these supports, The ATLAS-Japan group has been making intensive R&D’s on the detector upgrades and the KEK cryogenic group has started the R&D of the LHC separation dipole magnet.

![Graph showing LHC luminosity plan for the next decade](image)

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

In this context, at the end of 2010 CERN created the High Luminosity LHC (HL-LHC) project [5]. Started as a design study, and 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 June 2014, HL-LHC has become CERN’s major construction project for the next decade.

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 peak luminosity of $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ with levelling, allowing:
- 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 2023-2025, while taking all actions to assure a high efficiency in operation until 2035.

In 2013 the release of an updated long-term LHC schedule led to the concept of an enhanced annual integrated luminosity goal. If the target performance of 3000 fb$^{-1}$ is be reached by around 2035, as inferred by the European Strategy Update, the nominal goal of 250 fb$^{-1}$/year as fixed above is probably no longer adequate with the reduction in running time implied by the new schedule.
However, since all equipment is being designed with a margin of 50% with regard to the luminosity reach, the concept of ultimate parameters has been defined. By exploiting the margins one should be able to push the HL-LHC machine performance to a levelled luminosity of about $7.75 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$. This would imply an increase in the pile-up 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 work was initiated quite early: ideas were circulating at the beginning of the LHC construction [6] and continued throughout the LHC construction [7,8,9,10,11]. From 2003 the U.S.-LARP (see 1.3.2) has been the main and continuous motor for technological development devoted to the LHC upgrade. After a period during which the upgrade was conceived in two phases, all studies were unified in 2010 under the newly formed High Luminosity Project. The first step consisted in launching a Design Study under the auspices of EC-FP7 with the nickname of HiLumi LHC, which following the approval by EC in 2011, 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:

$$L = \gamma \frac{n_{b} N_{b}^{2} f_{\text{rev}}}{4\pi \beta^{*} \varepsilon_{n}} R; \quad R = \left( \frac{1}{1 + \frac{\theta_{c} \sigma_{x}}{2 \sigma}} \right)$$

- $\gamma$ 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$\times 10^{11}$ p (≈0.58 A of beam current at 2808 bunches)
- $f_{\text{rev}}$ is the revolution frequency (11.2 kHz)
- $\beta^{*}$ is the beam beta function (focal length) at the collision point (nominal design 0.55 m)
- $\varepsilon_{n}$ is the transverse normalized emittance (nominal design: 3.75 $\mu$m)
- $R$ is a luminosity geometrical reduction factor (0.85 at a $\beta^{*}$ of 0.55 m of, down to 0.5 at 0.25 m)
- $\theta_{c}$ is the full crossing angle between colliding beam (285 $\mu$rad as nominal design)
- $\sigma, \sigma_{x}$ are the transverse and longitudinal r.m.s. sizes, respectively (nominally 16.7 $\mu$m and 7.55 cm respectively)

With the nominal parameter values shown above, a luminosity of $1\times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ is obtained, with an average pile-up (number of events in the same bunch crossing) of $\mu = 27$ (although $\mu=19$ 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 2019 (after LS2). Any potential limitations coming from the LHC injector complex 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 ($\beta^*$ limit) and from the acceptable pile-up level. The ultimate value of bunch population with the nominal LHC should enable a peak luminosity of around $2 \times 10^{34}$ 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.

- **Inner Triplet Magnets:** After about 300 fb$^{-1}$ some components of the inner triplet quadrupoles and their corrector magnets will have received a dose of 30 MGy, entering into the region of possible radiation damage. The quadrupoles may withstand a maximum of 400-700 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 a 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 and magnet 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 removal of the power converters and associate DFBs (electrical feed-boxes, delicate equipment presently in line with the continuous cryostat) out of the tunnel, possibly to the surface. LHC availability should be improved. Displacement of power converters to distant locations is possible only 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:
  
  o **Quench Protection System** of the superconducting magnets, based on a design that is almost 20 years old.
  
  o **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 system will need renovation after 2020.
  
  o **Remote manipulation**: the level of activation from 2020 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 on the ground, remote manipulation, enhanced reality and supervision is 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 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: 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).](image)

Because of the levelled luminosity limit, to maximize the integrated luminosity one needs to maximize the fill length. This can be achieved 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 1-1 lists the main parameters foreseen for the high luminosity operation. The 25 ns bunch spacing is the baseline operation mode; however, 50 ns bunch spacing is kept as a possible alternative in case the e-cloud or other unforeseen effects undermine the 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 \( I_{\text{beam}} = 0.86 \, \text{A} \), 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 ultimate 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 as 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.
Table 1-1: High Luminosity LHC parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal LHC (design report)</th>
<th>HL-LHC 25ns (standard)</th>
<th>HL-LHC 25ns (BCMS)</th>
<th>HL-LHC 50ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy in collision [TeV]</td>
<td>7</td>
<td>2.2E+11</td>
<td>2.2E+11</td>
<td>3.5E+11</td>
</tr>
<tr>
<td>$N_b$</td>
<td>1.15E+11</td>
<td>2.2E+11</td>
<td>2.2E+11</td>
<td>3.5E+11</td>
</tr>
<tr>
<td>$f_b$</td>
<td>2808</td>
<td>2748</td>
<td>2604</td>
<td>1404</td>
</tr>
<tr>
<td>Number of collisions in IP1 and IP5</td>
<td>2808</td>
<td>2736 $^1$</td>
<td>2592</td>
<td>1404</td>
</tr>
<tr>
<td>$N_{coll}$</td>
<td>3.2E+14</td>
<td>6.0E+14</td>
<td>5.7E+14</td>
<td>4.9E+14</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.58</td>
<td>1.09</td>
<td>1.03</td>
<td>0.89</td>
</tr>
<tr>
<td>$\beta$ [m]</td>
<td>285</td>
<td>590</td>
<td>590</td>
<td>590</td>
</tr>
<tr>
<td>beam separation [rad]</td>
<td>9.4</td>
<td>12.5</td>
<td>12.5</td>
<td>11.4</td>
</tr>
<tr>
<td>$\beta^* [m]$</td>
<td>0.55</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$\epsilon$ [eVs]</td>
<td>3.75</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>r.m.s. energy spread</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
</tr>
<tr>
<td>r.m.s. bunch length [m]</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
</tr>
<tr>
<td>IBS horizontal [h]</td>
<td>80 -&gt; 106</td>
<td>18.5</td>
<td>18.5</td>
<td>17.2</td>
</tr>
<tr>
<td>IBS longitudinal [h]</td>
<td>61 -&gt; 60</td>
<td>20.4</td>
<td>20.4</td>
<td>16.1</td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td>0.65</td>
<td>3.14</td>
<td>3.14</td>
<td>2.87</td>
</tr>
<tr>
<td>Geometric loss factor R0 without crab-cavity</td>
<td>0.836</td>
<td>0.305</td>
<td>0.305</td>
<td>0.331</td>
</tr>
<tr>
<td>Geometric loss factor R1 with crab-cavity</td>
<td>(0.981)</td>
<td>0.829</td>
<td>0.829</td>
<td>0.838</td>
</tr>
<tr>
<td>peak luminosity without crab-cavity [cm$^{-2}$ s$^{-1}$]</td>
<td>1.00E+34</td>
<td>7.18E+34</td>
<td>6.80E+34</td>
<td>8.44E+34</td>
</tr>
<tr>
<td>Virtual luminosity with crab-cavity: Rpeak*R1/R0 [cm$^{-2}$ s$^{-1}$]</td>
<td>(1.18E+34)</td>
<td>19.54E+34</td>
<td>18.52E+34</td>
<td>21.38E+34</td>
</tr>
<tr>
<td>Events / crossing without levelling and without crab-cavity</td>
<td>27</td>
<td>198</td>
<td>198</td>
<td>454</td>
</tr>
<tr>
<td>Leveled luminosity [cm$^{-2}$ s$^{-1}$]</td>
<td>-</td>
<td>5.00E+34 $^2$</td>
<td>5.00E+34</td>
<td>2.50E+34</td>
</tr>
<tr>
<td>Events / crossing (with leveling and crab-cavities for HL-LHC)</td>
<td>27</td>
<td>138</td>
<td>146</td>
<td>135</td>
</tr>
<tr>
<td>Peak line density of pile up event [event/mm] (max over stable beams)</td>
<td>0.21</td>
<td>1.25</td>
<td>1.31</td>
<td>1.20</td>
</tr>
<tr>
<td>Leveling time [h] (assuming no emittance growth)</td>
<td>-</td>
<td>8.3</td>
<td>7.6</td>
<td>18.0</td>
</tr>
<tr>
<td>Number of collisions in IP2/IP8</td>
<td>2808</td>
<td>2452/2524 $^1$</td>
<td>2288/2396</td>
<td>0$^3$/1404</td>
</tr>
<tr>
<td>$N_b$ at SPS extraction $^2$</td>
<td>1.20E+11</td>
<td>2.30E+11</td>
<td>2.30E+11</td>
<td>3.68E+11</td>
</tr>
<tr>
<td>$f_b$ / injection</td>
<td>288</td>
<td>288</td>
<td>288</td>
<td>144</td>
</tr>
<tr>
<td>$\epsilon_c$ at SPS extraction [µm] $^1$</td>
<td>3.40</td>
<td>2.00</td>
<td>&lt; 2.00</td>
<td>2.30</td>
</tr>
</tbody>
</table>

1 Assumining 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 emittance 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.
\( \beta^* \) and cancelling the reduction factor \( R \): A classical route for a luminosity upgrade is to reduce \( \beta' \) by means of larger aperture and higher field low-\( \beta \) triplet quadrupoles. However a reduction in \( \beta' \) 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 \( \beta \)-functions inside the triplet magnets may furthermore exceed the strength of the existing correction circuits. The peak \( \beta \)-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 \( \beta^* \) 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 \( \beta^* \) value of 15 cm can be envisaged and a flat optics with a \( \beta^* \) as low as 5 cm in the plane perpendicular to the crossing plane could be realized. For such a \( \beta' \) reduction the triplet quadrupoles need to double their aperture, and required a peak field 50% above the present LHC. This implies the use of new, advanced, superconducting technology based on Nb$_3$Sn.

The drawback of very small \( \beta^* \) is that it requires a larger crossing angle. The drawback of very small \( \beta^* \) is that it reduces the geometrical luminosity reduction factor, \( R \). In Figure 5 the reduction factor is plotted vs. \( \beta^* \) values.

![Image](image_url)

**Figure 5:** Behaviour of geometrical luminosity reduction factor vs. \( \beta^* \) 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 \( \theta /2 \), 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 \( \beta^* \) values offered by the ATS scheme and the larger triplet quadrupole magnets. While the primary function of the crab cavities is to boost the virtual peak luminosity, they can also be used in combination with dynamic \( \beta^* \) variation during the fill. This would allow 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: Effect of the crab cavity on the beam (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 detector, ATLAS and CMS, see Fig. 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 inner 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.

Given the yearly and long-term operations schedule, the targets of 250 fb\(^{-1}\) per year and 3000 fb\(^{-1}\) by the mid-2030s are very challenging. If the performance of the HL-LHC can go beyond the design levelled luminosity value of \(L_{\text{peak}} = 5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) then these targets become more reasonable. 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 \(7.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) with levelling (see above for ultimate parameters). With a performance of 300 fb\(^{-1}\)/year, this would allow almost 4000 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 HL-LHC era, for the case of ultimate HL-LHC parameters. Note that for sake of simplicity there is no learning curve for the luminosity after LS3.

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, the 11 T dipole for DS collimation in P2 (for ions) and the SC links in P7 would be already installed during LS2.

The HL-LHC schedule is based on the following milestones, see Figure 9:
- 2014: Preliminary Design Report (PDR)
- 2015: end of design phase, release of the first Technical Design Report (TDR)
- 2016: Proof of main hardware components on test benches
- 2017: Testing of prototypes (including crab cavity test in SPS) and release of TDR_v2 (TDR in final version, for construction)
- 2017-2021: Construction and test of long lead hardware components (e.g. magnets, crab cavities, SC links, collimators)
- 2020-2022: String test of Inner triplet
- 2023-2025: LS3 – Main installation (new magnets, crab cavities, cryo-plants, collimators, absorbers, etc.) and commissioning
Figure 9: Schematic representation of the main HL-LHC milestones

The preliminary cost-to-completion (CtC) of the full HL-LHC project amounts to about 830 MCHF for Material (CERN accounting). A coarse evaluation of personnel requirements amounts to more than 1000 FTE-y. The cost-to-completion does not include the civil engineering works for the underground cavern (presently under evaluation) and non-baseline systems such as the long range beam-beam compensators and the RF harmonic system and the related infrastructures. The budget profile is shown in Figure 10.

Figure 10: Budget allocation 2015 - 2025

Today the CERN draft budget attributes about 750 MCHF for the HL-LHC project until 2025, with certain assumptions of in-kind contributions from both the USA and Japan. The discrepancy is not critical at this stage, since modifications of certain systems are not yet fully defined. LHC operation at full energy and intensity will give important indications. The thorough investigation of potential synergy with the LHC consolidation project together with various studies should allow savings without compromising performance. Additional in-kind contributions to the hardware baseline would help alleviate the cost discrepancy and would also bring more personnel into the project.

A further possibility is to stage the project by using LS4, see Figure 8. Indeed the performance “forecast” of Figure 8 is somewhat theoretical: there will be certainly a learning curve to pass from 2 to (levelled) $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, naturally favouring a staged approach. However, the 250 fb$^{-1}$ annual integrated luminosity goal can only be attained, and possibly even surpassed, when installation of all equipment is completed.
3 The Collaboration

The LHC Luminosity Upgrade was conceived from the beginning as 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. 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 (SLH-PP and EuCARD) helped to reinforce the design and R&D work for the LHC upgrade in Europe, although still at a modest level. KEK in Japan, in the frame of the permanent CERN-KEK collaboration, also engaged in 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 FP-HiLumi 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](image)
3.1 FP7-Hilumi LHC

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 US 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 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 thirteen 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 fully financed, with a EU contribution of M€4.9 against a request of M€4.97.

![Figure 22: 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).](image)

In Figure 13 the list of the 15 FP7-HiLumi Institutions is shown, followed by the list of the five USA collaborating institutes.
Figure 33: Table of the 15 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 US 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 US 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 Nb₃Sn 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 (Figure 14) 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$/year with 50% of the funding going directly to magnet development. Several magnets developed by LARP reached and surpassed the design field as shown in Figure 15 right for one of the latest models (HQ02, a 120 mm aperture quadrupole assembled in
2014 and tested at FNAL and CERN). Additionally, LARP has demonstrated the scale-up of the Nb$_3$Sn technology (i.e. the performance of the technology for magnets as long as 3 m) as shown in Figure 15 left for the LQ (90 mm aperture Long Quadrupole). The achievements of the US programs, in particular LAR but also of the general R&D high field magnet program, have led to the adoption of the Nb$_3$Sn superconductor solution as the baseline for the HL-LHC new focusing system and 11 T magnets.

**Figure 44:** Left: Improvement in Jc (Current Density) in Nb3Sn superconductor during the last 3 decades compared with the NbTi Jc performance. Right: Evolution of LARP quadrupole models showing the increase in bore diameter up to the HQ generation (120 mm aperture).

**Figure 55:** Left: Quench performance of LQ (Long Quadrupole), the first quadrupole demonstrating the scale-up of the Nb$_3$Sn technology to lengths of interest for LHC applications (~3 m). Right: Quench performance of HQ02 (120 mm aperture) after several re-assemblies, showing that in all cases the magnet achieved and passed the target (80% of the Short Sample Limit, SSL).

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 (Chapter 4) 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 CY15-CY17 period, LARP will concentrate on prototyping the elements needed by the HL-LHC project in which the US National Laboratories and Universities have demonstrated excellent capabilities. This prototyping phase is expected to continue until the start of construction in the 2018-2022 period.
3.3 KEK

Within the framework of the CERN-KEK collaboration, KEK has conducted the Nb$_3$Al 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$_3$Al superconductors have been 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 it was judged in 2011 that the Nb$_3$Al superconductor was unfortunately not ready for the industrialization for the HL-LHC upgrade anticipated around 2022.

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 research activities on the Nb$_3$Al superconductor development, 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.

3.4.1 CEA

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$_3$Sn at CERN).
- Studies on Nb$_3$Sn thermal properties and a finite element model of Nb$_3$Sn 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 inner 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 which have parallel direction in both apertures. 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 inner triplet. It features two dipoles coils, rotated by 90 degree 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 arborescence, 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. In Figure 16 the general governance of the project is shown. 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 2 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.

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 15 members (beneficiaries in FP7 terminology) of FP7-HiLumi LHC. The USA laboratories are not members of FP7-HiLumi LHC, however representatives of each USA laboratory, included the LARP Director, are co-opted in the enlarged Collaboration Board. The formal link with the USA 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 under study and will be operative from November 2015 when the FP7 Consortium Agreement comes to an end.

Figure 16: The general governance scheme of FP-7 HiLumi LHC, used for the whole HL-LHC project (see text for details)

In Figure 17 the project structure with all WPs and their coordinators, as well as the main collaborators, is shown. Typically, each WP is assigned 3 to 6 tasks. The tasks are the core of the technical work.
Figure 17: 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.

5 References


