THE HIGH LUMINOSITY LHC PROJECT[1]

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Abstract

This presentation reviews the status of the high luminosity LHC project, and highlights the main challenges from the technology and beam physics point of view. It will mention the outcome of the 2015 Cost and Schedule review for the HL-LHC project and summarizes the status of the high field quadrupole and crab cavity development.

HL-LHC PERFORMANCE GOALS AND SCHEDULE

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 2012. The LHC underwent from 2013 to 2015 a general consolidation of the magnet bus bar interconnections and started the second operation phase, the LHC RunII, in 2015 with beam energies of 6.5 TeV (→ CM collision energy of 13 TeV).

The full exploitation of the LHC 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 ten-fold increase of the nominal design value (300 fb^{-1} → 3000 fb^{-1}). The required machine modifications require new technologies and novel operation concepts. 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; long high-power superconducting links with zero energy and the operation with novel optics schemes and leveled luminosity. The necessary developments require substantial prototyping and testing.

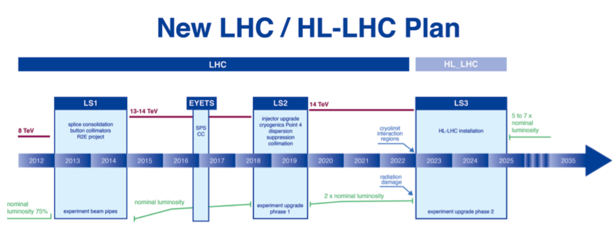

Figure 1: The LHC Baseline Program until 2025.

Figure 1 shows schematically the LHC baseline program until 2025 and Fig. 2 shows the potential evolution of the peak and integrated luminosities. 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 $L = 10^{34}$ $cm^{-2}s^{-1}$. This peak value should give a total integrated luminosity of about 40 fb^{-1} per year. In the period from 2015 to 2022 the LHC will hopefully further increase the peak luminosity by exploiting upgrades implemented during the second long shutdown LS2. These upgrades include the Phase I upgrade of the LHC experiments and a full implementation of the LHC Injector complex Upgrade (LIU) project, opening the door to an operation beyond nominal bunch intensities and beam brightness. Margins in the design of the nominal LHC are expected to allow, in principle, about two times the nominal design performance.

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 capability, the LHC will need to have a decisive increase of its luminosity.

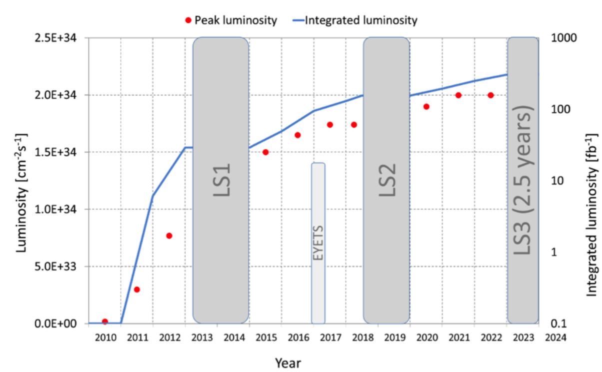

Figure 2: The projected evolution of peak and iterated luminosities over the LHC and HL-LHC project phases.

LHC LIMITATIONS AND HL-LHC CHALLENGES

The performance reach of the LHC beyond that of RunIII is limited by six fundamental limitations:

- Technical Bottle Necks
- Insertion Magnets: Lifetime and Aperture
- Crossing Angle and geometric reduction factor: Crab Cavities
- Performance optimization: Event rate and pileup density
- Beam power and particle losses
- Machine efficiency and availability

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The paper will briefly comment on each limitation within the following sub-sections.

Technical Bottle Necks

The key technical bottle necks for a performance increase of the LHC General Purpose (GP) detectors beyond that of RUNIII are the magnet lifetime of the triplet assembly, the capacity of the local heat exchanger inside the triplet magnets and the total available cryogenic power for the insertion magnets next to the experiments.

The radiation dose inside the triplet magnets will reach approximately 30MGy by the time the LHC accumulates a total integrated luminosity of 300 fb^{-1}. A radiation dose of this order of magnitude is assumed to define the maximum lifetime of the triplet assembly (mainly true to radiation exposure of the triplet corrector magnets) and the HL-LHC project therefore plans for a replacement of the existing triplet assembly with a more radiation hard assembly that can withstand the radiation dose implied by a tenfold increase of the total integrated luminosity.

The performance limit of the existing LHC triplet heat exchanger tubes is estimated at approximately $L = 1.7 \times 10^{34} cm^{-2}s^{-1}$. The HL-LHC project tackles this limitation via the installation of higher capacity heat exchanger tubes for the new triplet magnets and an additional 18kW cryo plant at the locations of each of the two GP experiments.

Insertion Magnets

The key modification of the HL-LHC project is the installation of new, large aperture triplet quadrupole magnets that provide aperture margins for a further reduction of the optical β functions at the Interaction Points (IPs) (β^*) and space for the installation of shielding inside the magnet cold bore that limits the radiation dose to the magnet coils to values similar to those expected to the nominal LHC magnets after RunIII but while reaching a ten times larger total integrated luminosity (3000 fb^{-1}).

Additional aperture inside the triplet magnets is also required for reducing the optical β functions at the IPs from the nominal values of 50cm to 15cm in both planes and to increase the crossing angle at the interaction points from the nominal 285 μrad to 590 μrad. The later is required in order to keep the non-linear fields from the parasitic beam encounters under control (see the next sub-section for more details).

Addressing the two above limitations in the design of the HL-LHC triplet quadrupole magnets led to the decision of designing the triplet quadrupole magnets with a total coil aperture of aperture 150mm (slightly more than twice the coil aperture of the nominal LHC magnets). Keeping the magnet gradient, the key operational quadrupole operational parameter unchanged at the with respect to the nominal LHC triplet, 210 T/m, would result in unfeasible peak fields of 16T at the magnet coils. At this time there is no superconducting cable technology capable of sustaining such high fields in an accelerator grade magnet design. The established accelerator magnet technology is based on NbTi superconducting capables and is capable of reaching 8-9 T at the coils (nominal LHC magnet design). Higher peak fields at the coils requires new technologies for the superconducting cable. One very promising candidate is Nb_3Sn technology (see Figure 3 for reference). However, this is a new technology for the design of accelerator grade magents with very different characteristics as compared to NbTi (e.g. brittle materials versus elastic fibers) requiring significant R&D efforts for the development for accelerator grade magnet construction.

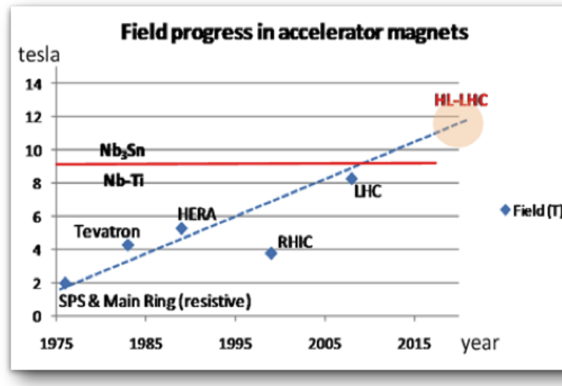

Figure 3: The performance reach of superconducting magnets for the NbTi and Nb_3Sn technologies versus time [1].

To meet this challenge a coordinated magnet R&D project was launched within the US in 2003. The USLARP effort lead to the design of 120mm diameter magnet prototype using a new structure based on bladders and keys [2]. This design has been scaled to a coil diameter of 150mm in 2014 and should be able to sustain a peak field at the coil of slightly above 11.5T for an operating gradient of 132 T/m. The smaller gradient with respect to the nominal LHC triplet magnets implies an approximately 30% longer triplet assembly for the HL-LHC insertions, leading to a total triplet assembly length of ca. 70m. This increase in length results in an increase of the number of unwanted parasitic beam-beam encounters, that will be discussed in the following subsection. The increase of the total triplet-D1 assembly length is partially (the beams only reach a sufficient beam separation by the middle of the separation dipole magnet) compensated by the use of shorter, superconducting separation (D1) and recombination (D2) dipole magnets at the interaction points that guide the two LHC beams from one aperture to the other when crossing the IPs. Figure 4 shows the comparison between the nominal and the HL-LHC triplet layouts.

Crossing Angle and Geometric Reduction Factor: Crab Cavities

The 25ns bunch spacing in the LHC implies potential beam-beam encounters every 3.75 meters wherever the two LHC beams share a common vacuum pipe. The total dis-

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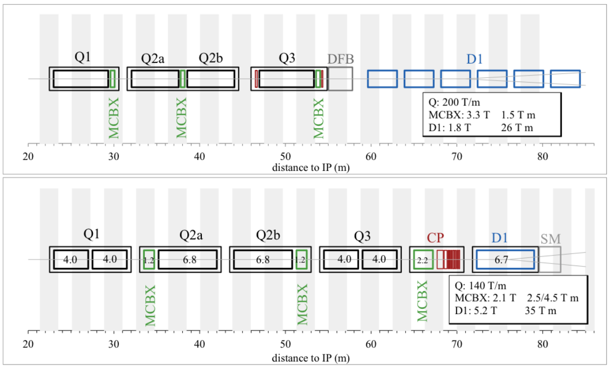

Figure 4: Comparison of the nominal and HL-LHC triplet layouts with the D1 dipole magnets. top: the nominal LHC layout. Bottom: the new HL-LHC layout.

tance between the triplet magnets left and right from the IP amounts to approximately 45m. Together with a triplet length of approximately 50m one obtains a total length of approximately 140m where the two beams follow the same reference trajectory yielding more than 36 unwanted parasitic collision points for each of the new HL-LHC Interaction Regions. The reference trajectories of the two beams separate only gradually over the length of the D1 magnet and the D1 magnet of the HL-LHC insertions adds a few more parasitic encounters for each IR. A external crossing angle is used to separate the two beams at the location of these parasitic encounters. Each particle experiences a non-linear field due to this 'interaction' and a separation of more than 11σ, where σ refers to the RMS beam size in the plane of separation of the two LHC beams, requiring a total crossing angle of $\theta = 590\ \mu$rad for the HL-LHC operation with $\beta^* = 0.1$m. Unfortunately, the crossing angle also reduces the luminous region and increases the effective cross section of the two beams at the IP. The net result is a reduction of the luminosity given by the expression in Equation (1) where σ_z is the RMS bunch length and σ_{crossing} the transverse RMS beam size in the plane of the crossing angle.

$$F = 1/\sqrt{1+\Theta}, \quad \text{with} \quad \Theta = \frac{\theta\sigma_z}{2\sigma_{crossing}}. \qquad (1)$$

Figure 5 illustrates the resulting luminosity reduction as a function of β^* assuming a constant, normalized beam separation of 10σ along the common drift space between the triplet assemblies.

While the geometric luminosity reduction factor is only marginal for the nominal LHC operation (approximately 10%), it becomes quite significant for β^* values below 0.3m, rendering the potential luminosity gain for HL-LHC with low-β operation essentially futile.

The HL-LHC project plans to use so called Crab Cavities, transversely deflecting RF devices, for tilting the LHC bunches transversely in the plane of the crossing angle, re-establishing effectively head-on collisions at the IPs and eliminating the geometric luminosity reduction factor. Figure 6 illustrates the effect of the crab cavities on the bunch collisions at the IPs.

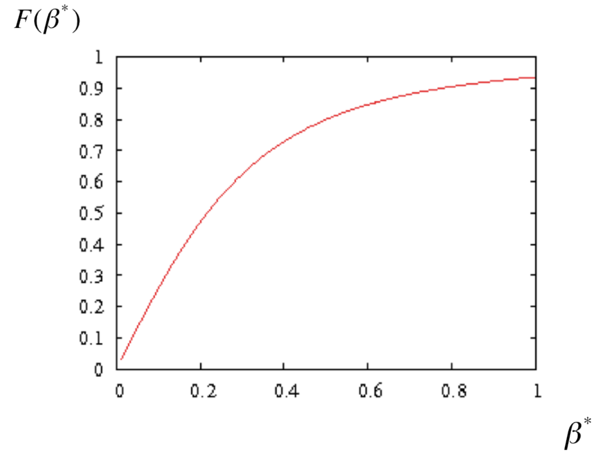

Figure 5: Geometric luminosity reduction factor F as a function of β^* assuming a normalized beam-beam separation of 10σ across the common drift space of thte two beams between the triplet assemblies and neglecting contributions front he Hourglass effect.

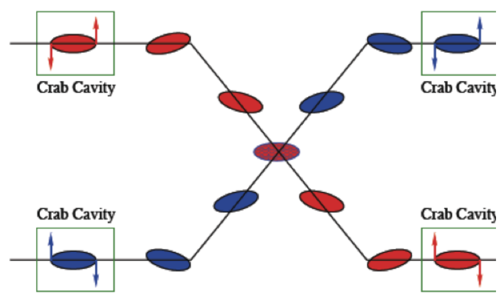

Figure 6: Illustration of the effect of Crab Cavities on the bunch orientation at the IPs. The Crab Cavities effectively generate head-on collisions at the IPs and thus, avoid the loss of luminosity due to the beam crossing angle.

Crab Cavities have first been proposed by Bob Palmer [3] and have first been successfully used in an accelerator for the KEK B-factory [4] [5] [6]. However, KEK-B is a lepton machine with strong radiation damping and sufficient transverse space for elliptical RF cavities. The LHC, on the other hand, is a proton machine with only moderate radiation damping (increasing significantly the worry about the effect of RF noise on the beam performance) and with limited space constraints (the two be am aperture are only separated by 192mm at the experimental insertions). The first point requires a demonstration of the operability of Crab Cavities and controllability of RF phase noise in these devices for use in a Hadron storage ring. The second point requires a novel cavity design which differs from the conventional elliptical design used in most SC RF systems. A collaboration effort between CERN, SLAC, BNL, Old Deminon University and

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Lancaster University in the UK lead to the development of three cavity prototypes. All three prototypes have successfully reached the specified operating field in a vertical test cryostat. In order to meet the tight timeline of performing cavity tests with beam prior to the launch of the final production for the HL-LHC, a HL-LHC Crab Cavity review selected two of these designs for further prototype development and the design of a cryostat with 'dressed' cavities that includes couplers, HOM dampers and tuners compatible with beam tests in the SPS following the technical stop of 2016-2017. Both selected prototypes have successfully exceeded the required operating gradients at recent tests in the US and at CERN [7]- [9].

Performance Optimization: Total Event Rate and Pileup Density

Maximizing the virtual performance reach of the HL-LHC and the beam lifetime during physics fills asks for the maximum possible beam current in the machine (the beam lifetime for a given leveled luminosity is directly proportional to the total stored beam current [10]), leading for the operation with 25 ns bunch spacing to a bunch intensity of 2.2×10^{11} particles per bunch and a total beam current of more than one ampere (1.09 A per beam). With a normalized emittance of 2.5 μm and $\beta^* = 15$ cm this results in a virtual peak luminosity of $L = 20 \times 10^{34}\mathrm{mc}^{-2}\mathrm{s}^{-1}$ when one assumes that the geometric luminosity reduction is avoided through the use of Crab Cavities.

However, the main experiments demand two, partially contradicting requests for the HL-LHC upgrade project. On the one hand, the experiments ask for a tenfold increase in the integrated luminosity with respect to the nominal LHC, leading to a total integrated luminosity request of $3000\mathrm{fb}^{-1}$ and an annual integrated luminosity of ca. 250 fb^{-1} per year. This requests clearly asks for the highest possible luminosity in the HL-LHC machine. On the other hand, the experiment would like to limit the number of events per bunch bunch crossing to an average value of 140 with peak values of up to 200 events per crossing. This, on the other hand, translates directly into a limitation of the maximum acceptable bunch luminosity. For the operation with 25ns bunch spacing this limit of the maximum number of events per bunch crossing limits the peak luminosity in the HL-LHC machine to $L = 5 \times 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The approach of tackling these partially contradicting requests is to operate the machine with a leveled luminosity, where the machine is designed for a potential virtual performance reach that is significantly higher than the value imposed by the maximum number of events per bunch crossing and where the operational luminosity is continuously adjusted, leveled, to the maximum acceptable value for the experiments. The operation with high virtual and leveled luminosity keeps the maximum number of events per bunch crossing and the pile-up density within the limits of the experiments while maximizing the potential run length and thus, the integrated luminosity per fill.

Initially it was foreseen to use the Crab Cavities and the adjustment of the effective crossing angle at the IP for this leveling. However, in addition to the total number of events per bunch crossing, the experiments would also like to limit the longitudinal event density, the so called pile-up density, to less than one event per mm. Adjusting the crossing angle at the IP with Crab Cavities changes the total luminosity, but leaves unfortunately the pile-up density unchanged. The use of Crab Cavitites for the luminosity leveling is therefore to a viable option of the HL-LHC.. Instead, the HL-LHC foreseen now an operation with full compensation of the crossing angle via Crab Cavities and leveling of the luminosity through a continuous adjustment of β^* during operation. This operation mode has already been preliminarily tested during machine studies in the LHC, but still requires further developments during the coming operation years of the LHC.

Beam Power and Losses

The operation with 25ns bunch spacing and a bunch intensity of 2.2×10^{11} particles per bunch translates to a total beam current of $1.09A$ and a total stored beam energy of more than 500MJ for each of the two HL-LHC beams. These beam energies are significantly beyond the LHC quench and damage limits and imply that even losses of the beam halo can cause beam aborts and equipment damage. The HL-LHC addresses these challenges with two complementary approaches. First of all, the HL-LHC project foresees a reinforcement of the collimation system by installing additional absorbers and collimators in sensible locations. For example, the installation of new, so called cryo collimators in the dispersion suppressors (DS) left and right of the experiments and the cleaning insertions minimizes the debris that can reach the cold magnets in the arcs. Second, the HL-LHC project studies an active control (depletion) of the beam halo, for example, through the use of a hollow electron lens that continuously enhances the diffusion speed of particles in the beam halo and thus, reduces the halo density. The net outcome of this halo depletion is a reduction of the losses during short drops in the beam lifetime and, or small jitters in the beam trajectories (for example during the ramp and adjust mode of the LHC operation or due to external perturbations [e.g. earth quakes]). However, at this stage this is not yet in the HL-LHC baseline and only studied as an option.

The cryo collimator installation in the DS requires the replacement of one 15 meter long 8T LHC dipole magnet by two 5.3 meter long 11T strong Nb_3Sn magnets. The shorter Nb_3Sn magnets provide the same deflection angle as a nominal LHC dipole magnet and leave approximately 2.2 meter 'free' space for the installation of collimators inside the dispersion suppressor region. The development of 11 T dipole magnets was initially done in collaboration with FERMILAB in the US but is currently conducted at CERN. The development of a hollow electron lens for the depletion of the beam halo is done in collaboration with FERMILAB and is supported through the USLARP program.

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Machine Efficiency and Availability

Achieving the HL-LHC goal of 250 fb^{-1} per year and a total integrated luminosity of 3000 fb^{-1} over the HL-LHC operation phase requires a the maximum possible machine efficiency and availability. One possible measure of the machine efficiency is to look at the ratio of actual time spend in physics production versus the actual time spend in physics production (another measure could be to look at the ratio between the actually produced luminosity versus the theoretically possible maximum value that one could obtain if one assumes the optimum fill length for each fill and minimum possible time for the preparation of a new fill).

The operational experience of LHC RunI showed that only 30% of all fills had been terminated by operators. All other fills had been terminated either by equipment failure or beam losses and the machine efficiency reached only values of ca. 40% in 2011 and 2012. One important contribution to premature beam aborts is equipment failure due to Single Event Upsets (SEU) coming from Radiation to Electronics (R2E) that is installed in the LHC underground areas. The first LHC operation phase in featured in total ca. 12 beam aborts per fb^{-1} integrated luminosity, resulting in approximately 400 hours down time. Additional shielding and relocation of sensitive equipment reduced the SEUs to approximately 3 beam aborts per fb^{-1}. Further optimizations during the first long shutdown (LS1) of the LHC from 2013 to 2014 should lead to a further reduction of the SEUs, aiming at a beam abort rate of ca. 0.5 aborts per fb^{-1}

Reaching the HL-LHC performance goals clearly requires an improvement of these numbers and lead for the HL-LHC to a extensive consolidation program of all LHC equipment and a new paradigm where as much as possible active equipment (electronic cards) will be removed from the tunnel. For example, the HL-LHC foresees the use of superconducting links that allow the removal of all power converters from the underground areas to the surface or to new galleries adjacent to the tunnel, while minimizing the resistive losses due to the long distances of the powering cables. These additional measures aim at a reduction of SEUs to less than 0.1 beam abort per fb^{-1} integrated luminosity.

PROJECT STATUS

The HL-LHC project is an international study lead by CERN. Partners include the US LHC Accelerator Research Program (US-LARP) that coordinates research activities of four major US laboratories (BNL, FERMILAB, LBNL and SLAC) for the development of the new Nb_3Sn triplet quadruple magnets, Crab Cavities and wide band feedback systems; Old Dominion University in Virginia, USA for the development of Crab Cavities; KEK in Japan for the development of new, superconducting, single aperture D1 separation dipole magnets; Spain for the development of the dipole corrector magnets inside the triplet assembly; Italy for the design of non-linear corrector magnets next to the triplet assembly and new, superconducting 2-in-1 D2 combination dipole magnets; France for the development of new, large aperture matching section quadrupole magnets and the UK for the development of Crab Cavities. Furthermore, the general HL-LHC design study is supported by an EU funded international collaboration, HighLumi, that has as the main objective the establishment of the HL-LHC baseline and the publication of the HL-LHC Conceptual Design Report (CDR) by the end of 2015. The EU funded Design study will end at the end of 2015 and a Preliminary Design report (PDR) is already under publication. Table 1 summarizes some of the key HL-LHC parameters.

Table 1: Key HL-LHC Parameters

Parameter	**LHC Value**	**HL Value**
N_b	1.15×10^{11}	2.2×10^{11}
n_b	2808	2748
Norm. Emittance	3.75 μrad	2.5 μrad
Long. Emittance	2.5 eV − s	2.5 eV − s
Crossing angle	285 μrad	590 μrad
β^*	0.55 m	0.15 m
Virtual Lumi	$1.2 \times 10^{34} cm^{-2}s^{-1}$	$2 \times 10^{35} cm^{-2}s^{-1}$
Events / crossing	27	138
Opt Fill Length	8 h	10 h

The HL-LHC project enters therefore in 2015 the transition from a Design Study to a Construction Project. This transition has been accompanied in 2014 by the approval of CERN council of the HL-LHC financial plan up to 2025 and by several key project reviews in 2014 and 2015. The budget approval by CERN's council forms the prerequisite for the official launch of the HL-LHC production phase. Two technical the reviews for the superconducting cable and the triplet magnet design looked at the viability of the new triplet magnet design. A general external Cost and Schedule review by an international review committee followed in March 2015 (together with a review of the accompanying LIU project for the upgrade of the LHC injector complex). All reviews certified the HL-LHC and the LIU projects a good bill of health and the HL-LHC project is now well prepared for the transition from the design phase to the production phase of the project. Figure 7 shows the general project planning for the HL-LHC project.

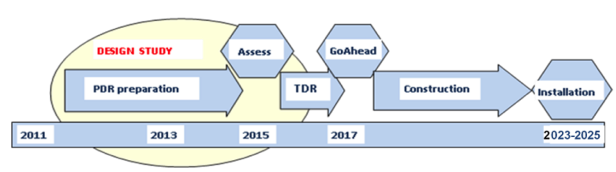

Figure 7: Illustration of the general timeline for the HL-LHC project implementation.

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