https://doi.org/10.1142/9789811278952_0001

Chapter 1

The High Luminosity Large Hadron Collider – HL-LHC*

O. Brüning[a] and L. Rossi[b]

[a]*CERN, ATS-DO Unit, Genève 23, Switzerland*
[b]*University of Milano and INFN-LASA Milano, Italy*

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 10,000 scientists. To extend its discovery potential, the LHC requires 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. Being a highly complex and optimized machine, such an upgrade of the LHC must be carefully studied and requires about 10 years to implement. The novel machine configuration, called High Luminosity LHC (HL-LHC), relies on a number of key innovative technologies, each 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 100-metre-long high-power superconducting links with negligible energy dissipation, very precise 2-Q high current power converter, new surface treatment for e-could suppression, and many others. All these constitute major breakthroughs in accelerator technology.

* The Project has been initially partially supported by the EC as *FP7 HiLumi LHC Design Study* under grant no. 284404. The HL-LHC Project is mainly supported by CERN with special in-kind contributions and support by: USA-DOE (HL-LHC-AUP, with FNAL, BNL, LBNL and SLAC laboratories), KEK-Tsukuba (Japan), INFN-LASA-Milano and INFN-Genova (Italy), CIEMAT-Madrid (Spain), STFC-Daresbury (UK, with participation of Huddersfield, Lancaster, Liverpool, Manchester, Oxford, Royal Holloway and Southampton Universities), IHEP-Beijing (CN), BINP-Novosibirsk and PNPI-St Petersburg (Russian Federation) until the end of 2021, Uppsala University (SE), TRIUMF-Vancouver B.C. (CA) and PAEC (Pakistan).

HL-LHC federates efforts, R&D, and construction of a large community in Europe, the USA, Japan, China and Canada, thereby consolidating CERN and LHC as the center of a world-wide collaboration for basic science and technology.

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. It delivered 8 TeV center-of-mass proton collisions from April 2012 until the end of the LHC Run1 in 2012 and pushed the collision energy to 13 TeV center-of-mass during the Run2 period from 2015 until 2018. The LHC is pushing the limits of human knowledge: the discovery of the Higgs boson in 2012 is undoubtedly a major milestone in the history of science.

Thanks to the LHC, Europe has decisively regained world leadership in high-energy physics, a key sector of knowledge and technology development. The LHC can continue to act as catalyst for a global effort: out of the 12400 CERN users, about 8700 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 until 2025, when it is expected that several key components in the LHC machine and Detectors will reach the end of their radiation lifetime at around 400 fb^{-1} integrated luminosity, and the HL-LHC will assure this position for another decade up to 2040. Its full exploitation is the highest priority of the European Strategy for particle physics, adopted by the CERN Council in 2013 and revised in 2020, and is a reference point for the Particle Physics Strategy of the US and for various other States worldwide. To extend its discovery potential, the LHC needs a major upgrade in the 2020s to extend its operability by another decade or more, and to increase its collision rate and thus integrated luminosity. The upgrade design goal is a five-fold increase in the instantaneous collision rate and a ten-fold increase of the integrated luminosity (the total data volume). As a highly complex and already well-optimized machine, such an upgrade must be carefully devised, and actually calls for breakthroughs in a variety of critical collider technologies. The necessary developments require focused research efforts, extending to over 10 years for studies, prototyping, testing, and construction of new equipment.

HL-LHC federates the efforts and R&D of a large international community towards the ambitious HL-LHC objectives and contributes to establishing CERN as a focal point of global research cooperation and leadership in frontier knowledge and technologies. HL-LHC relies on strong participation from various partners beyond CERN, with important in-kind contributions by Non-Member States laboratories in the USA, Japan, China, and Canada, and by Member States leading Institutions/Universities: INFN (Genova and Milano-LASA Italy), CIEMAT (Madrid, Spain), STFC (UK) and other British Universities and Institutions, Uppsala University (FREIA Laboratory, Uppsala, SE), and several other partner institutes. These participations with in-kind contributions, as well as the participation of other Institutes providing skilled personnel and studies, are key ingredients for the execution of the construction phase. The US LHC Accelerator R&D Program (LARP) has been essential for the development of some of the key technologies for the HL-LHC, such as the large-aperture niobium–tin (Nb_3Sn) quadrupoles and the crab cavities.

The LHC baseline program till 2025 is schematically shown in Figure 1, together with the initial HL-LHC exploitation time. After entering in the near-to-nominal energy regime of 13 TeV center-of-mass energy during Run2 in 2015, LHC has reached the design luminosity[†] of 10^{34} cm^{-2} s^{-1} in 2016 and attained the so-called ultimate luminosity $L_{ult} = 2\times10^{34}$ cm^{-2}s^{-1} in 2018, where the cryogenic limit in the inner quadrupole triplet magnets was reached. In terms of integrated luminosity, about 65 fb^{-1} were collected during the 2018 operation year, bringing the total integrated luminosity of LHC to nearly 190 fb^{-1}. The most sensible projection is to reach about 350 fb^{-1} (and maybe even 400, in case of very smooth operation) by end of Run3 in 2025 which exceeds the LHC design luminosity of 300 fb^{-1} and is assumed to come close to the expected equipment lifetime due to the implied radiation for several key elements in the LHC machine and the main detectors.

In addition to the consideration of radiation damage to the machine and detectors, as indicated in Figure 1, that would require serious long interventions, after 2025 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 halve the statistical error in the measurements will be more than ten years after 2025. Therefore, to

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

Fig. 1. LHC/HL-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 2019-2021, is for secure luminosity and reliability as well as to upgrade the LHC Injectors. After LS3, in 2029 the machine will be in the High Luminosity configuration (HL-LHC) and operates till nearly 2040.

maintain scientific progress and to explore its full capacity, the LHC will need to have a decisive increase of its luminosity. Somehow the necessity of an important luminosity upgrade was already inscribed in the LHC design, well before its operation. That is why, when the CERN Council adopted the European Strategy for Particle Physics in 2006 [1], it was agreed the first priority was "*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 was confirmed as *first priority* among the "High priority large-scale scientific activities" in the European Strategy for Particle Physics update in 2013 [3] and underlined by the CERN Council in June 2016, when it approved the HL-LHC as an official Upgrade Project at CERN. The European Strategy for Particle Physics update in 2020 reiterated the high priority of the HL-LHC with the following words: *"The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques."*

The importance of the LHC upgrade in luminosity for the future of High Energy Physics was also affirmed in the 2014 Snowmass process (the USA process of the strategy of particle physics). In the May 2014 resolution of the so-called P5 panel in the USA [4], a critical step was taken 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, at the end of 2010 CERN put in place 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 by CERN Council on 30 May 2013 and the insertion of the budget in the CERN Medium Term Plan, approved by the Council in June 2014. Then, in 2015, the Council approved the HL-LHC budget for the period 2016-2021 (MTP2015) and positively acknowledged the remaining HL-LHC budget for the years 2022-2026 in the so-called long term plan information included in the MTP document, for a total of 950 MCHF of material budget. Eventually, the CERN Council approved the entire HL-LHC project, with a total material budget of 950 MCHF for 2015-2026, in the session of June 2016 [7], as one of the first key decisions of Fabiola Gianotti's directorate. Significantly, the High Luminosity LHC is the first project with explicit approval as a stand-alone project by the Council after the LHC.

The main objective of High Luminosity LHC, as established in the HiLumi LHC submission to EC in the Seventh Framework Programme (FP7-INFRA) of November 2010 [8] 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 levelling, 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 (2026-2028) and commissioning the new machine configuration in 2029.

All hadron colliders in the world prior to the LHC have so far produced a total combined integrated luminosity of about 11 fb^{-1}. As reported above, LHC has delivered so far nearly 190 fb^{-1} and should reach and exceed 350 fb^{-1} by 2026. The High Luminosity LHC is a major and extremely challenging upgrade. For its successful realization, several key novel technologies have to be developed, validated, and integrated. The work initiated with the FP7 Design Study HiLumi LHC which, approved by EC in 2011 with the highest mark [9], was instrumental in initiating a new global collaboration for the LHC that matches the spirit of the worldwide user community of the LHC experiments.

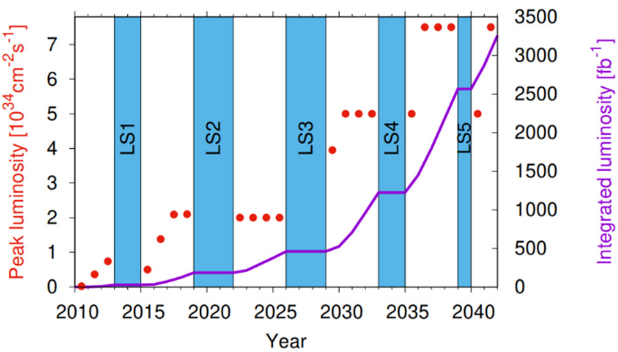

Fig. 2. Luminosity evolution for LHC, extrapolated until end of Run3 and projected for the HL-LHC both in terms of peak and integrated luminosity.

The High Luminosity LHC project is working in close connection with the companion ATLAS and CMS upgrade projects of 2019-2028 and the upgrade of LS2 for both LHCb and ALICE, as discussed in [10]. Furthermore, the performance of the high luminosity machine critically depends on the performance of the injector chain as well, whose main upgrade finished in 2020 under the companion program, the LHC Injector Upgrade (LIU) [11] and the complex has been commissioned in the 2021 and 2022 machine running periods.

2. Approach for the Upgrade

The (instantaneous) luminosity L can be expressed as:

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

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 2760 for 25 ns
N is the bunch population. $N_{\text{nominal 25 ns}}$: 1.15×10^{11} p ($\Rightarrow$ 0.57 A of beam current at 2760 bunches)
f_{rev} is the revolution frequency (11.2 kHz)
β^* is the beam beta function (focal length) at the collision point (nominal LHC design 0.55 m)
ε_n is the transverse normalized emittance (nominal LHC 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 LHC design)
σ, σ_z are the transverse and longitudinal r.m.s. size, respectively (16.7 μm and 7.6 cm).

2.1. *Present luminosity limitations and hardware constraints*

There are various 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 has been completed and fully commissioned during the Run3 period. Any potential limitations coming from the LHC injector complex put aside, it was expected that LHC would have reached performance bottlenecked by the beam current and cleaning efficiency at 350 MJ stored beam energy and from the acceptable pile-up level. LHC was supposed to reach the maximum luminosity level of $L = 2\times10^{34}$ cm^{-2}s^{-1} only with the ultimate value of bunch population (1.7×10^{11} p/bunch). This maximum luminosity value (sometimes called ultimate luminosity for the LHC) was established in the LHC design as the maximum compatible with the heat deposited in the Inner Triplet (IT) quadrupoles by the collision debris escaping along the beam pipe. Beyond this peak luminosity value, the heat can no longer be removed sufficiently fast from the magnets. This value has actually been reached already in Run2 with a bunch population approximately at nominal value, 1-1.2×10^{11} but with smaller than nominal optical beta functions at the IP and smaller than nominal beam emittances. The reason this was possible was because the magnet aperture is better than anticipated and that the beam emittance delivered by the injectors in LS2 exceeded any expectations: 2.2 μm instead of 3.5 μm for LHC nominal design intensities thanks to the novel Batch Compression Merging Scheme (BCMS) implemented in the PS [12]. This allowed β^* of 25-30 cm to already be reached in Run2 and made it possible to reach ultimate luminosity much earlier than anticipated. However, the luminosity limit from heat removal appeared exactly as expected, and this means that the peak luminosity cannot increase. This limit was predicted in 2003, based on computations extrapolated from Tevatron experience [13] and based on cryogenic computations. The slight difference of the actual limiting value of 2×10^{34} cm^{-2}s^{-1} wrt the initially expected 2.5×10^{34} cm^{-2}s^{-1} is due to the fact that an accident on the IT heat exchanger during the hardware commissioning [14] forced a smaller heat exchanger to be retrofitted, which reduced the heat removal capability of the system by 15-20%. Another intrinsic limit, also reported in [15], is that the dose on the triplet would reach the radiation damage limit at around 350-400 fb^{-1}. The radiation damage is not a hard limit. The magnets may still work well above 400 fb^{-1}, especially if the collision configuration is adapted (e.g. changing of the crossing angle [16]). However, running above 400 fb^{-1} implies entering a dangerous zone where a magnet fault can cause an unanticipated long shutdown with bad consequences for the LHC operation and the data taking at the experiments.

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 regular on-going consolidation work.

(1) *Inner Triplet Magnets*: As previously mentioned, at about 350-400 fb^{-1} some components of the low-beta triplet quadrupoles and their corrector magnets will have received a dose of 30 MGy, entering the region of radiation damage. The quadrupoles may withstand 400-700 fb^{-1}, but some corrector magnets of nested type might already wear out at above 350 fb^{-1}. The numbers are difficult to compute exactly because of uncertainties on material properties and on exact heat deposition locations that strongly depend on the detailed collision conditions, such as the crossing angle that varies from fill to fill and during a fill. Regardless, damage must be anticipated because the most likely way of failing is through a sudden electric breakdown, entailing a magnet replacement with a serious

and long intervention in an extremely challenging radiation environment and confined space that requires a careful and time-consuming intervention preparation. Replacing a single triplet may take almost one year: the worst thing for the LHC is a long shutdown that was not planned and where other maintenance and upgrade activities cannot be implemented. That is why replacement of the triplet must be envisaged before actual damage occurs. In addition, if one magnet fails, the other ones are probably close to failing soon as well, i.e. all the triplets in the two high luminosity insertions, P1 and P5, need to be replaced at the same time. Since triplet replacement in one IP (8 quads) requires more magnets than the total spare magnet pool (4 quads) a production of additional magnets would need to be started well in advance. Replacement of the low-beta triplets is a long intervention, requiring at least one year, and must be coupled with a major detector upgrade. Also, the detectors suffer from radiation damage in the Inner Tracker system, whose performance degrades strongly after 350-400 fb^{-1}. The LHC has been designed to have a common lifetime, or to require a synchronized major maintenance, both for accelerator and detectors, in the high luminosity insertions.

(2) *Cryogenics*: To increase flexibility and balance the power availability for each magnet sector (and thus to maximize the integrated luminosity for a given cryogenic power) we plan to upgrade the cryo-plant in P4. We have abandoned the pursuit of full separation between superconducting RF cavities and magnets cooling. However, the increased capacity of the P4 plant eliminates an initial limitation, especially in view of the higher than expected power consumption in the LHC cold bore tube, driven by e-cloud effects and probably due to bad surface condition. The main cryogenic aspect that may penalize the LHC performance in terms of luminosity in the long term is the coupling of the cooling of the inner triplets (and matching section) magnets with the magnets of the arc. Decoupling the insertion region cooling from one part of the arc would avoid warming up the entire arc in an intervention in the triplet region (an operation of 3 months and not without risk). In addition, the total power available for the insertion region is about 250 W per side of each interaction point, which for P1 and P5 is insufficient to go beyond 2.5-3×10^{34} $cm^{-2}s^{-1}$.

(3) *Collimation and absorbers*: The collimation system has been designed for the first phase of LHC life and has performed very well. The new collimators installed during LS1 with beam position monitors integrated in the jaws have drastically reduced the setting-up time. However, in view of the higher intensity beams of HL-LHC, a reduction of the impedance is also needed (the collimator jaws account for ca. half the impedance of the total machine). Therefore, many secondary collimators will be replaced with new lower impedance ones, based on a newly developed MoGr (molybdenum – graphite) composite with a Mo coating. The tertiary collimators protecting the triplets must also be changed. Any small gain in triplet aperture and performance must be accompanied by an adequate consolidation or modification of the collimation system, including a number of collimators and masks intercepting physics debris. A second area that will require a special attention for the collimation system is the Dispersion Suppressor (DS), 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 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 gained space is sufficient for placing special collimators. There is actually another concept which has been demonstrated in Run2, which uses crystals to kick the off-momentum particles towards larger amplitudes, such that the secondary collimators can do the job with less complexity and cost. However, this only works for ions. After LS3, when the full HL-LHC beam will be deployed, only the operational experience of Run3 can show if DS collimators, and thus 11T magnets, are required for the proton operation during the HL-LHC exploitation, depending on the observed minimum beam lifetimes. The Injection protection absorbers also need to be replaced with better ones, called TDIS: the higher modularity of the new ones, along with improved robustness, is necessary to deal with the intense new LIU beams. The main fixed absorbers for the collision debris also need to be replaced, following the new magnet aperture. New TAXS and TAXN absorbers are being designed for IR1 and IR5, and even in IR8 a new TAN is needed to accommodate the increased luminosity of LHCb experiment (from 4×10^{34} cm^{-2}s^{-1} to 2×10^{33} cm^{-2}s^{-1}).

(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 especially, but not only, for the electrical power converter feeding the magnets. A complementary solution is also pursued for the new magnets in IR1 and IR5: removal of the power supplies and associated DFBs (electrical feed-boxes, delicate equipment today in line with the continuous cryostat and containing the current leads) out of the LHC tunnel. Displacement of power converter (and electrical feed-boxes) into lateral new galleries, suitably excavated, is possible without excessive power consumption and increasing the voltage drop at power converter terminals, thanks to a novel technology, Superconducting links (SCLs) whose main body is made out of MgB_2 superconductors.

(5) *Other Systems:* Other systems will become a bottleneck along with aging of the machine and a higher performance with > 60 fb^{-1} per year. Among the most critical are the Halo control, the Beam Dump system and the injection system.

2.2. *The high luminosity parameters and upgraded systems*

2.2.1. *Luminosity levelling 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 levelling. As shown in Figure 3 (left), without levelling, the luminosity profile 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 that is lower than the maximum obtainable peak luminosity i.e., “levelling” the instantaneous luminosity and avoiding its decay for a good part of the fill, the average luminosity is almost the same - within 20-25% - as the one of a run with higher peak luminosity and without levelling, see Figure 3 (right). However, this has the big advantage of a smaller maximum peak luminosity.

The fact that the maximum levelled luminosity is limited means that in order to maximize the integrated value, one needs to maximize the run length,

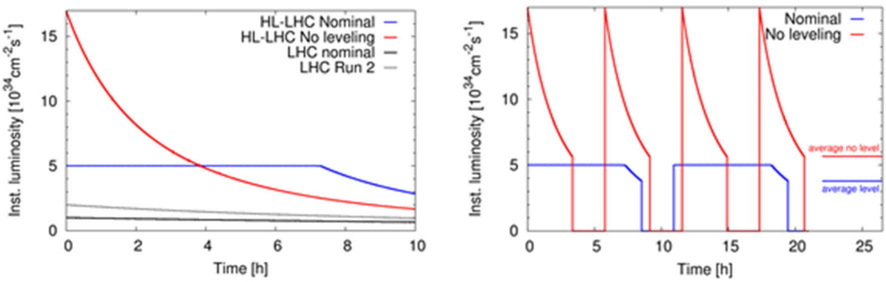

Fig. 3. Left: luminosity profile for a single long run for: LHC nominal peak luminosity (black line), LHC Run2 at ultimate luminosity (grey line), HL-LHC no levelling (red line) and HL-LHC with levelling (blue line). Right: luminosity profile with optimized run time, without (red line) and with levelling (blue line) with indication of the average luminosity for both cases.

which can be obtained by filling the maximum number of protons, i.e. by maximizing the beam current: $I_{beam} = n_b \times N$ and minimizing unintentional aborts in the beam operation due to equipment faults. Other key factors for maximizing the integrated luminosity and obtaining the challenging goal of exceeding 3 fb^{-1}/day are: a short average machine turnaround time (the time from end of a fill and start of collision in the successive fill), and a good overall machine "efficiency", defined as the ratio between actual luminosity produced and the luminosity of a continuous ideal cycle (see Figure 4). Clearly, for maximizing the integrated luminosity, the efficiency matters almost as much as the virtual peak performance. We call the maximum value that one could obtain in principle at the beginning of the fill before proton burning starts to decrease it, the "virtual luminosity". For example, looking at Figure 3 (left), one can see that HL-LHC virtual luminosity is 17×10^{34} $cm^{-2}s^{-1}$, i.e. seventeen times the nominal LHC luminosity. Somehow, the ration between virtual and levelling luminosity gives the idea of the "luminosity reservoir" one can use to continue the levelling.

For the levelled luminosity operation, one injects the beam with the current and emittance values fit for reaching the virtual peak luminosity. However, one or more of the machine parameters controlling the luminosity are "detuned" i.e. not set to the values for maximum luminosity production. This is kept as a "reserve". Then during the luminosity run, these parameters are slowly "retuned" toward their optimum values to compensate the proton burning (or other source of luminosity loss, like emittance increase). Typical

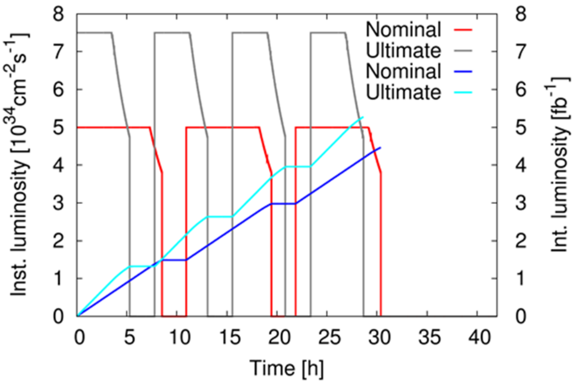

Fig. 4. Luminosity cycle for HL-LHC with levelling and a short decay (optimized for integrated luminosity) assuming 100% efficiency. The set of parameters generating cycle are the 25 ns column of Table 1.

parameters we intend to use as knobs for levelling are the optical beta function at the IP, controlling the beam size at collision (β^*), the crossing angle, and the overlap of the two beams at the IP.

HL-LHC with scheduled 160 days of physics operation needs an efficiency of ca. 50% to reach the HL-LHC goal of 250 fb^{-1} per year. During Run2 the efficiency was pretty stable at values around 50% (with the notable exception of 2015, the start-up year after LS1). However, one has to account for the increased complexity of HL-LHC, with levelling operation, the addition of new hardware (crab cavities, new refrigerator, etc…). Reaching an efficiency as high as achieved in the present LHC but with a (levelled) luminosity five times the nominal one, with much higher bunch population and additional technically complex hardware, will be a strong challenge. The project must therefore be accompanied by 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 for proton collisions. In order to mitigate possible limitations arising from heat deposition from e-cloud effects, HL-LHC maintains a backup scheme based on 25 ns bunch spacing and a filling sequence of 8 bunches followed by

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

Parameter	Nominal LHC (design report)	HL-LHC 25 ns (standard)	HL-LHC 25 ns (BCMS) [8]	HL-LHC 8b+4e [10]
Beam energy in collision [TeV]	7	7	7	7
N	1,15E+11	2,2E+11	2,2E+11	2,2E+11
n_b [12]	2808	2760	2744 [13]	1972
Number of collisions in IP1 and IP5 [1]	2808	2748	2736	1960
N_{tot}	3,2E+14	6,1E+14	6,0E+14	4,3E+14
Beam current [A]	0,58	1,1	1,1	0,78
Half Crossing angle [μrad]	142,5	250	250	250 [9]
Norm. long range beam-beam separation at minimum β*	9,4	10,5	10,5	10,5 [9]
Minimum β* [m]	0,55	0,15	0,15	0,15
ε_n [μm]	3,75	2,50	2,50	2,50
ε_L [eVs]	2,5	3,03	3,03	3,03
R.M.S. energy spread (q-Gaussian distribution)	-	1,10E-04	1,10E-04	1,10E-04
R.M.S. energy spread (FWHM equiv. Gaussian)	1,13E-04	1,29E-04	1,29E-04	1,29E-04
R.M.S. bunch length [m] (q-Gaussian distribution) [11]	-	7,61E-02	7,61E-02	7,61E-02
R.M.S. bunch length [m] (FWHM equiv. Gaussian) [11]	7,55E-02	9,00E-02	9,00E-02	9,00E-02
IBS horizontal [h]	105	16,5	16,5	16,5
IBS longitudinal [h]	63	19,2	19,2	19,2
Piwinski parameter	0,65	2,66	2,66	2,66
Total loss factor R0 without crab-cavity	0,836	0,342	0,342	0,342
Total loss factor R1 with crab-cavity	-	0,716	0,716	0,716
beam-beam / IP without crab-cavity	3,1E-03	3,3E-03	3,3E-03	3,3E-03
beam-beam / IP with crab-cavity	3,8E-03	8,6E-03	8,6E-03	8,6E-03

Table 1. (*Continued*)

Parameter	Nominal LHC (design report)	HL-LHC 25 ns (standard)	HL-LHC 25 ns (BCMS) [8]	HL-LHC 8b+4e [10]
Peak Luminosity without crab-cavity [$cm^{-2}s^{-1}$]	1,00E+34	8,1E+34	8,1E+34	5,8E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2}s^{-1}$]	-	1,70E+35	1,69E+35	1,21E+35
Events / crossing without levelling and without crab-cavity	27	212	212	212
Levelled Luminosity [$cm^{-2}s^{-1}$]	-	5,0E+34 [4]	5,0E+34	3,80E+34
Events / crossing (with levelling and crab-cavities for HL-LHC)	27	131	132	140
Peak line density of pile up event [event/mm] (max over stable beams)	0,21	1,28	1,29	1,37
Levelling time [h] (assuming no emittance growth) [7]	-	7,2	7,2	6,4
Number of collisions in IP2/IP8	2808	2492/2574 [6,13]	2246/2370 [13]	1178/1886 [13]
N at LHC injection [2]	1,20E+11	2,30E+11	2,30E+11	2,30E+11
n_b/injection	288	288	240 [13]	224
N_{tot}/injection	3,46E+13	6,62E+13	5,52E+13	5,15E+13
ε_n at SPS extraction [μm] [3]	3,5	2,1	1,7 [5]	1,7

[1] Assuming one less batch from the PS for machine protection (pilot injection, TL steering with short trains of nominal bunches) and non-colliding bunches for experiments (background studies…).
Note that due to RF beam loading the abort gap length must not exceed the 3μs design value.
[2] An intensity loss of 5% distributed along the cycle is assumed from SPS extraction to collisions in the LHC.
[3] A transverse emittance blow-up of 10 to 15% on the average H/V emittance in addition to that expected from intra-beam scattering (IBS) is assumed.
[4] For the design of the HL-LHC systems (collimators, triplet magnets...), a design margin of 50% on the stated peak luminosity was agreed upon.
[5] For the BCMS scheme emittances down to 1.7 μm are expected at LHC injection which might be used to mitigate excessive emittance blowup in the LHC during injection and ramp.

[6] 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.
[7] The total number of events/crossing is calculated with an inelastic cross-section of 81 mb (also for nominal), while 111 mb is still assumed for calculating the proton burn off and the resulting levelling time.
[8] BCMS parameters are only considered for injection and as a backup parameter set in case one encounters larger than expected emittance growth in the HL-LHC during injection, ramp and squeeze.
[9] The crossing angle for the 8b+4e alternative could be reduced down to about 400 μrad (9 σ) thanks to the lower number of long ranges.
[10] The 8b+4e variant represents a back-up scenario for the baseline 25ns operation in case of e-cloud limitations. The parameters are still evolving but are stated for the sake of performance reach comparison.
[11] The RF system is assumed to operate at 16MV with full detuning.
[12] The underlying assumption of reliable operation with a 200/800 ns SPS/LHC injection kicker rise time still remains to be proven during 2018 operation.
[13] Updated baseline filling schemes and inclusion of LHCb Upgrade II.

4 empty buckets [8b4e] or variations of it. The large extra heat load observed in a few LHC sectors during Run2 and triggered by e-cloud effects by still unidentified mechanisms, remains a possible threat to operation with HL-LHC bunch intensities and filling schemes. For similar reasons, a slightly different parameter set with very small emittance beams (BCMS) is also maintained in case the LHC operation at high beam intensities reveals unexpected sources for emittance blow-up during the beam injection and acceleration.

For ion collisions, there is a similar parameter table as described in Table 2 below, which lists three sets of parameters for the ions: the values from the original LHC design report, the HL-LHC baseline parameters assuming slip stacking in the SPS and an alternative third 75 ns option as backup.

Table 2. High Luminosity LHC parameters for ions.

Parameter	Nominal LHC (design report)	HL-LHC (baseline)	HL-LHC 75 ns option
Beam energy [Z TeV]	7	7	7
Number of bunches per beam	592	1240	733
Bunch spacing [ns]	100	50	75
Bunch intensity [10^7 Pb ions]	7	18	21
Stored beam energy [MJ]	3,8	20,5	14,2

Table 2. (*Continued*)

Parameter	Nominal LHC (design report)	HL-LHC (baseline)	HL-LHC 75 ns option
Total beam current [mA]	6,12	33	22,7
Normalized transverse emittance e_n [μm]	1,5	1,65	2,3
Longitudinal emittance ε_L [eVs/charge]	2,5	2,42	2,33
R.M.S. energy spread [10^{-4}]	1,1	1,02	1,06
R.M.S. bunch length [cm]	7,94	8,24	8,24
IBS horizontal [h]	13	5,8	10,8
IBS longitudinal [h]	7,7	2,6	2,8
Peak RF voltage [MV]	16	14	14
Number of colliding bunches (IP1/5)	<592	976 - 1240	733
Number of colliding bunches (IP2)	592	976 - 1200	702
Number of colliding bunches (IP8)	0	0 - 716	468
β* at IP1/5 [m]	0,55	0,5	0,5
β* at IP2 [m]	0,5	0,5	0,5
β* at IP8 [m]	10	1,5	1,5
Half crossing, IP1/5 [μrad]	160	170	160
Half crossing, IP2 (external, net) [μrad]	110, 40	170, 100	137, 60
Half crossing, IP8 (external, net [μrad]	-	-170, -305	160
Peak luminosity, IP1/2/5 [10^{27}cm^{-2}s^{-1}]	1	-	6,2
Levelled Luminosity, IP1/5 [10^{27}cm^{-2}s^{-1}]	-	6,4	-
Levelled Luminosity, IP2 [10^{27}cm^{-2}s^{-1}]	-	6,4	6,4
Levelled Luminosity, IP8 [10^{27}cm^{-2}s^{-1}]	-	1	1

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 operation.

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. Putting aside radiation effects, in principle, all systems have been designed for principle for $I_{beam} = 0.86$ A, the so called "ultimate" beam current. However, this has yet 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. Especially the power needed for the RF system is a concern. Operating the SRF cavity system in detuning mode and implementing high efficiency klystrons should solve this issue, but remains to be fully demonstrated.

For HL-LHC the beam brightness needs to be increased, which is a property that must be maximized at the beginning of the beam generation and then preserved throughout the entire injector chain and LHC itself. The LIU project has as primary objective to increase the beam brightness at the LHC injection, basically increasing the number of protons per bunch by a factor two above what was achieved in the injector complex during Run2, while keeping the emittance at the same low value.

β^* and cancelling the luminosity 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 larger aperture IT quadrupoles (implying a larger peak field at the coils), alongside an upgrade of the matching sections quadrupoles. A reduction in β^* values implies an increase of beam sizes inside the IT quadrupoles and a wider crossing angle, which, in turn, both require larger aperture IT quadrupole magnets, larger D1 and D2 separation/recombination dipole magnets and a few additional modifications in the matching section. Stronger chromatic aberrations coming from the larger β-functions inside the triplet magnets may exceed the strength of the existing correction circuits, and the peak beta-function inside the IT magnets is also limited by the possibility to match the optics to the regular beta functions of the neighbouring arcs. A previous study has shown that a practical limit in LHC is $\beta^* = 30$ cm, compared to the 55 cm foreseen in nominal operation and the 15 cm foreseen for HL-LHC. 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 for the chromaticity correction. 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, implying a peak field of 11-12 tesla, 50% above the present LHC, requiring a new, more performant superconducting technology based on Nb_3Sn.

Another drawback of operating with very small β^* values and a small bunch spacing is that it requires a larger crossing angle in order to avoid unwanted long-range beam-beam encounters. In addition to requiring aperture inside the IT magnets, a large crossing angle entails a reduction of the geometrical luminosity reduction factor 'R', see luminosity expression. In Figure 5 the reduction factor R is plotted for a constant normalized beam separation of 10 σ vs. β^* values. '+' signs indicated the value for LHC design, actual LHC 2018 Run2) and the value foreseen for HL-LHC (bottom cross along red line).

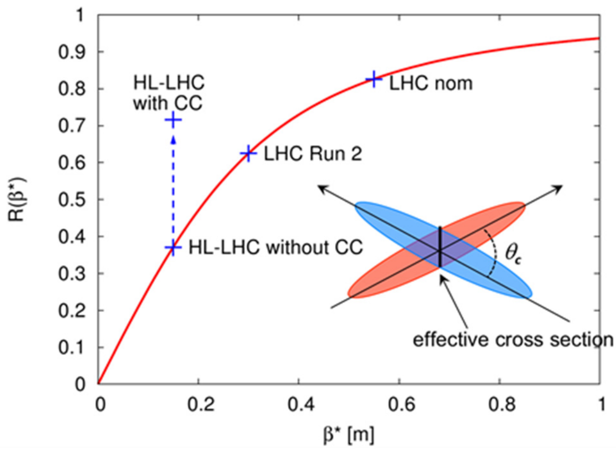

Fig. 5. Behavior of geometrical reduction factor of luminosity vs. β^* for constant normalized beam separation with indicated various operating points. The sketch of bunch crossing shows the reduction mechanism: a reduction of the luminous region [bunch overall] and an increase of the effective bunch cross section at the IP.

An efficient and elegant solution for compensating the geometric reduction factor is the use of special RF crab cavities, capable of generating a transverse electric field, a voltage kick, to rotate each bunch by as close as possible to $\theta_c/2$, such that they collide effectively head on, overlapping almost perfectly at the collision point, see Figure 6 even in presence of a crossing angle. Crab cavities make 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 therefore boosting the virtual peak luminosity for attaining the full HL-LHC performance. They can also be used as a levelling tool by varying the voltage kick, but unfortunately at constant pileup density. β^* levelling is therefore the baseline operation scenario, but the easy levelling or anti-levelling knob provided by the CC will certainly be an asset for operation.

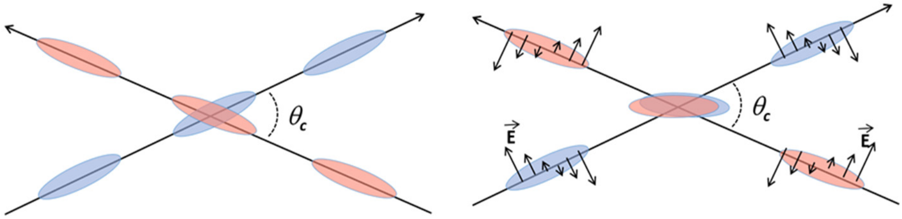

Fig. 6. Effect of the crab cavity on the beam: left, bunch collision geometry without CC; right: with CC small arrows indicate the transverse varying RF Electric field E when crossing the CC (please note that the E kick has same directions before and after collision; however, because of the almost 180 degree betatron phase advance between the two kicks, it correspond to an opposite torque on the bunch [π-bump].

3. New Equipment and Modifications for HL-LHC

The HL-LHC project tries to address all issues and hardware limitations described in Section 2.1. In this section, we list all new equipment that will be installed within the HL-LHC baseline and all modifications to the present LHC configuration: for a complete description of the equipment and configuration we redirect the reader to each article of this book and to the HL-LHC Technical Design Report [17]. There is some equipment that has been only recently added to the HL-LHC baseline [e.g. at the 2019 Cost & Schedule Review]. These items are listed in a separate dedicated section.

3.1. *Magnets and associate equipment*

3.1.1. *11T in Nb_3Sn (LS2)*

The LHC collimation system has a small but significant loss of particles that may deposit too much energy in the dispersion suppressor (DS) region, (see Chapter 8). This is a cold zone, part of the 3 km continuous cryostat: in particular, the first superconducting dipoles can be quenched in case of both ion beams and proton beams once the upgrade is carried out. As a mitigation measure of this problem, it has been considered to install collimators in the DS region. Since collimators need to be placed in a warm region, the only way to generate space in case the loss peaks occur in a region occupied by a dipole magnet, is to substitute an 8.4 T, 15 m long LHC dipole with two 11 T, 5.5 m long new LHC dipoles. The 4-meter free-space is enough to install a by-pass system connected to the 1.9 K continuous cryostat hosting at room temperature the 1-meter-long collimator. In P7 of the LHC, we need two systems, one on each side of the insertion, to protect the neighbouring superconducting arcs from the debris escaping from the collimation system in P7.

The 11 T dipole is a very complex new equipment since it requires use of more performant Nb_3Sn superconductors, the key technology also being used for the IT triplet upgrade. The aperture of the magnets is much smaller than the IT triplet, 60 mm vs. 150 mm. However, it is a double bore magnet, like all LHC main dipoles. In addition, the 11 T dipoles have a number of additional constraints because they are part of the regular LHC main dipole electrical and cryogenic circuits. For example, the current is powered in series with the arc magnets while the integrated transfer function must fit perfectly to the one of the LHC main dipoles.

Despite a big effort by the project and the technical teams, and in spite of the initial success of the short magnet development program, featuring the identical size in cross section as the full-size magnets, the initial full length 11 T dipoles (arranged in pairs of 5.5. m long dipoles, with a cold-warm-cold by-pass hosting the collimators in the middle), displayed some unexpected

Fig. 7. Two first 11 T dipoles of the series production under test at the CERN testing infrastructure called SM18.

behavior. Three of the first four dipoles tested at the CERN SM18 facility, see Figure 7, reached the nominal field but showed a peak field degradation after high power quenches and thermal cycles.

In light of these observed degradations, it has been decided to not install the 11T magnets until the origin of the effect has been fully understood and mitigated. In total, considering a full spare unit, six 11 T- 5.5 m long dipoles will be needed for HL-LHC. In parallel, the LHC operation will study in more detail the magnet quench limits in the existing machine and the actual need for the DS collimators during Run3.

Crystal collimators were added to the HL-LHC baseline at the end of 2019, in order to mitigate the risk of performance shortcomings of the 11T magnets. Crystal collimators effectively protect the superconducting arcs for operation with ion beams. However, the need for dispersion suppressor collimators for proton operation cannot be mitigated by the crystal collimators. A final decision on the need for the 11T dipoles for the HL-LHC proton operation will be taken during the LHC Run3 period when more operational data with higher beam intensities following the LIU upgrade in LS2 becomes available.

3.1.2. *IT quadrupoles in Nb_3Sn*

As mentioned in Section 2.2.2, a much larger aperture for the IT aperture is required for reaching very small β^* values. The aperture for HL-LHC IT quadrupoles has been selected to be 150 mm. Using Nb-Ti technology, as in the present LHC magnets, would mean unpractical magnet lengths, almost tripling the length of the present quadrupole triplets and resulting in unacceptably large peak beta function inside the triplets [chromatic aberrations] and generating problems for integration and layout with serious difficulties in other areas (for example requiring a stronger D1-D2 magnet pair). In practical terms, we have decided to go for a gradient and length combination that requires a peak field of about 11.5 T on the coil of the quadrupoles (for 7 TeV beam operation). As already cited, such a field imposes the use of Nb_3Sn superconductor, the only viable choice today for accelerator magnets beyond the 8.5-9 T operational limit of the NbTi technology. It also makes it easier to deal with the heat deposition by the collision debris due to the larger temperature margin of Nb_3Sn as compared to that of NbTi superconductor.

Each Triplet array consists of four cryo-assemblies: Q1, Q2a, Q2b and Q3, like in the LHC. The only difference, from a layout point of view, is the -limited- increase of the total triplet length (from 32 m to 42 m physical length). All Q1/Q2a/Q2b/Q3 magnets will be powered in series, and the cross section is the same for all quadrupoles. We will need four IT triplet assemblies, one per side of the two high luminosity insertions, P1 and P5. Only the magnetic length is different: 7.2 m for the Q2a/b and 8.4 m for Q1 and Q3 magnets. However, for reducing risk and technical difficulties for the Q1 and Q3 magnet production, under requests of our partner of US-HL-LHC-AUP in charge of the design and construction (see next section on collaboration), the Q1 and Q3 quadrupoles will be segmented into two magnets of 4.2 m length each, assembled in the same cold mass and cryostat. In Figure 8, a US quadrupole magnet, i.e. half of Q1 or Q3, is shown before testing. Including spare magnets, practically a fifth IT triplet assembly, the HL-LHC will need to manufacture 30 Nb_3Sn quadrupoles, 10 of 7.2 m length and 20 of 4.2 m length. The triplet assembly will be tested in advance with a special set up in the CERN Magnet Test Hall (SM18) as "HL-LHC IT String" to check installation and operational issues well before commissioning in the machine.

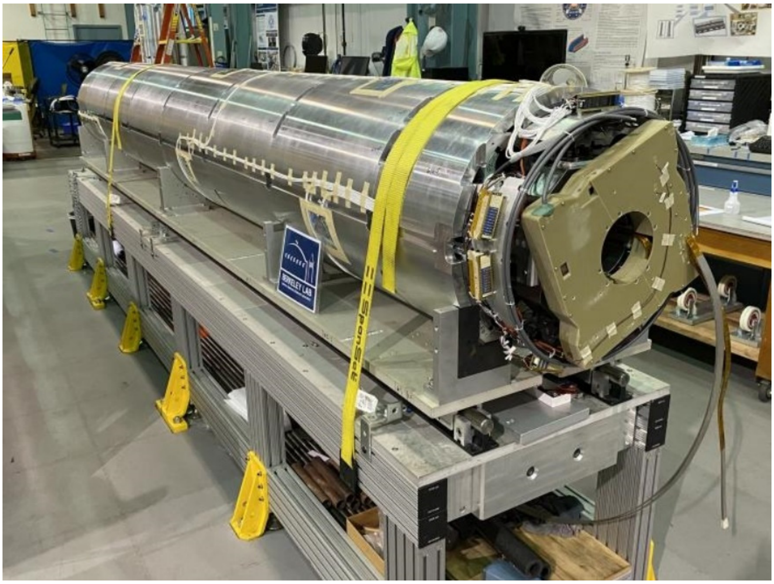

Fig. 8. MQXFA05 at Lawrence Berkeley National Laboratory, USA.

It is worth remembering that not only Nb_3Sn is a new, more complex, technology than the Nb-Ti deployed in the LHC. Because of their high peak field and especially because of their enormous aperture, the HL-LHC triplet magnets have forces and stored energies that are larger than the LHC main dipoles and comparable with dipoles considered for next generation hadron colliders, such as the FCC-hh, or for the main ring of a Muon-collider. This gives the measure of the technical challenge and explains why the HL-LHC is a pivotal project for the technological advancement for energy frontier colliders.

3.1.3. *IR magnets in Nb-Ti*

The increased aperture of the IT triplet requires revision of the aperture of many other magnets too. In the first layout of the HL-LHC, we planned to change almost all magnets of the insertion region, from Q1 down to Q5, with the noticeable exception of Q6. However, further studies and design optimizations allowed us to avoid the change of the Q4 and Q5 magnets. However, in addition to the IT triplet quadrupoles, an upgrade is still required for the separation/recombination dipole pair, called D1 and D2, and the numerous corrector magnets that are associated to the IT triplet quadrupoles and to the D1/D2 pair.

All these magnets are wound with Nb-Ti and operated at 1.9 K. The difficulties for these new magnets come from increased field and size or from the use of new coil/magnets layout as listed below:

(1) The 6 D1 separation dipoles (4 for installation and 2 spare ones) are single aperture magnets, featuring a peak field of almost 6 T and a length of more than 6 m. The coil aperture of 150 mm implies a stored energy per unit length of 0.35 MJ/m-aperture, sensibly larger than the 0.25 MJ/m-aperture of the LHC dipoles.
(2) The 6 D2 recombination dipoles (4 for installation and 2 spare ones) are double aperture magnets, with the same field direction in both apertures. Since their field and aperture, 4.5 T and 105 mm, are considerably larger than for the LHC D2 magnets, the field quality and coil design poses much bigger challenges than in LHC (cross talk) and the stored energy of 0.15 MJ/m-aperture is considerable for such magnets.

(3) The 18 single aperture orbit corrector magnets (dipoles with both horizontal and vertical orientation) for the Inner Triplets have fields similar to the ones in the LHC, but with much larger aperture. Like in the nominal LHC, these dipoles are of nested type, with two concentric dipole coils rotated by 90° with respect to each other. This design makes it very difficult to control tolerance and stress on the coils in presence of large torque: the outer dipole coils have a diameter of almost 200 mm, which poses serious mechanical challenges. The integrated field is 4.5 Tm, a value that makes it misleading to call it a simple "corrector" magnet.

(4) In total 54 single aperture magnets for the correction of high order (HO) field harmonics, from quadrupoles to dodecapoles errors, are needed for the HL-LHC Inner Triplet regions (the number of magnets includes some 14 spare magnets). These HO magnets will all be *superferric*: the main field is given by an iron pole-yoke circuit that is magnetized by small compact superconducting coils. In this way, one achieves the advantage of compactness, with sharp field decay (a key point because the 150 mm aperture is comparable to the needed magnetic length) and reduces the risk of radiation damage with respect to classical superconducting magnet designs. This configuration is a novelty, too, for colliders see Figure 9.

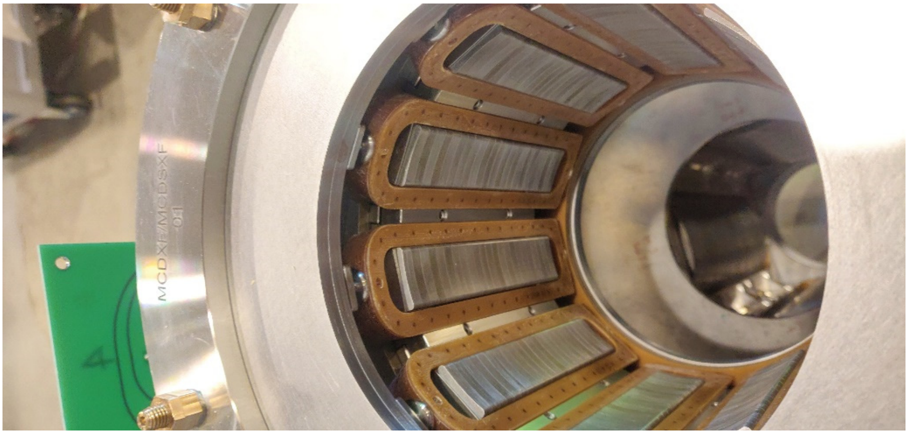

Fig. 9. Inside view of a superferric dodecapole corrector under assembly at INFN-LASA-Milano. Well visible are the rectangular coils surrounding the flat iron poles.

(5) The 12 double aperture orbit correctors that are assembled in the D2 cold mass will be made with a novel coil layout called Canted-Cosine-Theta (CCT) design, that generates the dipole field via two nested inclined solenoidal coils with opposite winding. The integrated field is 5 Tm, again a very big value for a "corrector" magnet. The length of nearly 2 m calls for a dipole field of 2.6 T, which makes this new magnet design potentially very attractive, which promises to considerably simplify the construction of superconducting magnets working at low-moderate field. This again is a novelty for Colliders, see Figure 10.

Fig. 10. Winding the first CCT prototype at CERN.

3.1.4. *Cold and warm powering*

The new magnet circuits need more electrical power converters (EPCs) that are newer and more powerful. They will be hosted in new, long galleries 8 m above and 30 m aside of the LHC tunnel to provide optimum protection against radiation from the tunnel and to facilitate the access during operation. The connection between EPCs and magnets, about 110-130 m long, will be made via superconducting links. Flexible cryostats host a cable composed of several cables made of MgB_2 superconducting strands. The use of new MgB_2 composite is a novelty for larger systems: it allows cooling via He gas operating between 4 and 20 K with higher temperature margin and much larger energy margin than classical Nb-Ti strands cooled with supercritical helium flow. Consequently, the superconducting links are very stable, almost insensible to quench and the use of gas accommodates for height differences between the EPCs and the magnets in the tunnel and also allows operators to access the galleries of the power converter during operation.

Fig. 11. Handling tests of a superconducting link.

The cold powering system, one of the most innovative technologies in HL-LHC, is then composed by cold distribution feedboxes (DFs for triplet magnets or DFMs for matching section magnets), hosting the connections between Nb-Ti bus bars coming from the magnets and MgB_2 cables. The long MgB_2 cables, starting from DF/DFMs, are located in a flexible cryostat ending into cold boxes placed in the higher-level galleries (called DFHs or DFHMs). Here the cables are spliced to short HTS cables that are connected to the He gas cooled copper current leads, the feedthrough realizing the passage from cold to warm powering. Finally, from current leads to the nearby EPCs the connection is made by heat-sink-cooled copper bars. Another new feature is that between current lead and EPCs, special "disconnector" boxes are inserted to facilitate the segregation of the circuits, and to improve electrical safety of operators.

The power converters are all of the same class of the LHC ones, except the 18 kA EPC for the new IT magnets that feature the novelty of being Class 0, i.e. better than 1 ppm ripple and ten times more precise than the ones deployed for the LHC main magnets. In addition, the 18 kA EPCs are of 2-Quadrant type. The 2-Q layout allows speeding up IT quadrupole current decrease, a new feature too, beyond present technology requiring new developments.

3.1.5. *Magnet and machine protection*

The protection systems of the HL-LHC feature advanced electronics control and radiation resistance boards in all domains. The main conceptual novelty is probably the use of the new CLIQ (Coupling Losses Induced quench) concept for the quench protection of the IT quadrupoles, together with classical quench heaters. In this case, it should be noted again, that it is the first time ever that the CLIQ concept is used to protect magnets in an accelerator. Its very short reaction time is very much suited to the high current density Nb_3Sn windings to spread the quench over the whole coil in a few milliseconds. Also, this is a key test in real conditions for a critical technology for FCC-hh magnets.

3.2. *Crab cavities*

As mentioned above, crab cavities are used for the first time on a hadron collider. For HL-LHC, they improve the bunch overlap at the interaction point (IP) and thus, compensate for the geometric luminosity reduction factor. Two

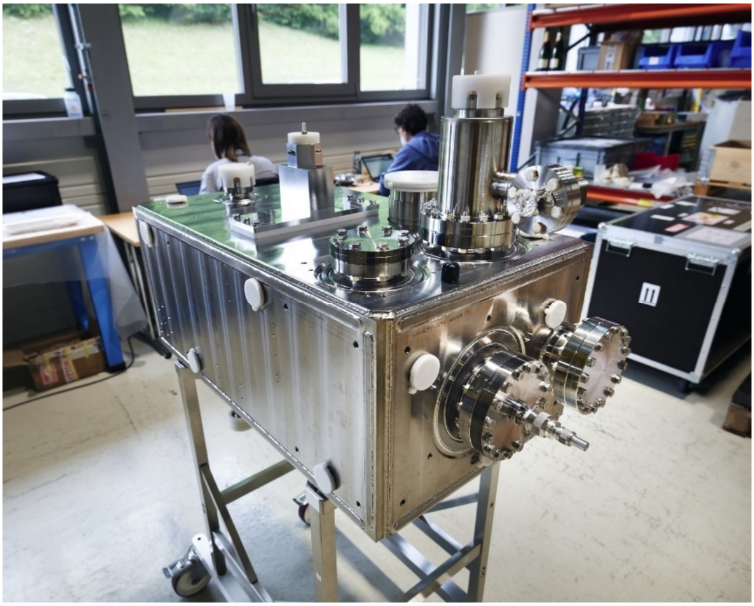

Fig. 12. RFD2 crab cavity within its magnetic shielding manufactured at CERN.

single cell cavities are placed on the incoming beam in the matching section at 160 m from the IP. Each cavity gives a kick of 3.3 MV, resulting in a nominal total kick of 6.6 MV for the incoming beam. A similar voltage kick is given to the outgoing beam (the same beam after collision) at the other side of the IP. Each crab cavity pair is hosted in one cryo-module: the distance between the two counter-circulating beams is so small that, in spite of the extremely compact design of the CC, the beam pipe of the non-kicked beam needs to be hosted in the cryo-module of the CC. Considering the two beams, we have the following layout (please note that vertical-horizontal crossing is opposite as it is in the present LHC):

(1) P1 (ATLAS, horizontal crossing beams): 4 cavities per IP side, of the RFD type. Two cryo-modules per side, one per beam.
(2) P5 (CMS, vertical crossing beams): 4 cavities per IP side, of the DQW type. Two cryo-modules per side, one per beam.

In total, considering that each type will require a spare cryo-module, we will have 10 CC cryo-modules, with in total 20 CC cells, half in DQW for vertical deflection at P5 and half in RFD for horizontal deflection in P1.

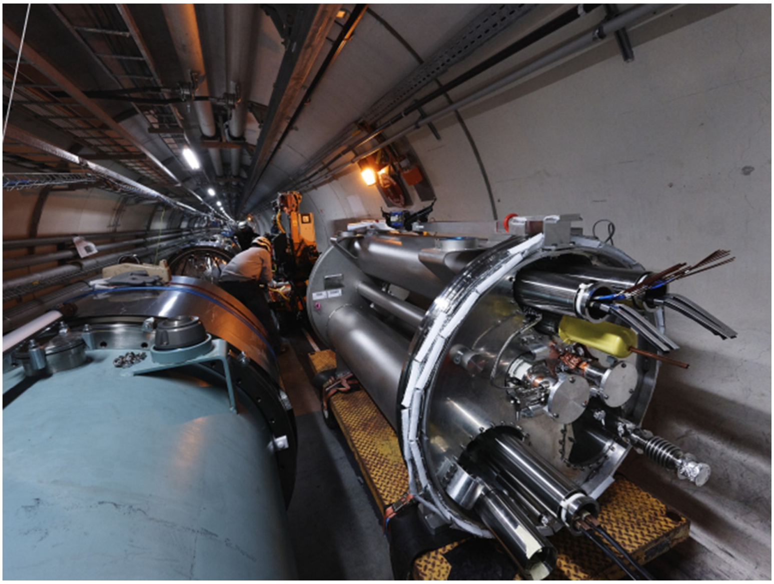

Fig. 13. Installation of a new bypass near the new cryostat installed in 11L2.

3.3. *Collimators (LS2 and LS3)*

The collimation system requires a serious upgrade to face the challenge of the more intense HL-LHC beams. The upgrade can be summarized as follows:

(1) Upgrade of 18 secondary collimators (8 during LS2) with new jaws, with active absorbing components made of a new molybdenum-graphite composite (MoGr) and then coated with molybdenum. The projected impedance reduction is a big step to assure stable beams with the required HL-LHC intensities.

(2) Upgrade of the tertiary collimation system (12 units) to cope with larger triplet aperture and increased robustness and the addition or upgrade of 8 collimators and 12 fixed masks to intercept debris form the IP. With the reuse of existing collimators, a total of 28 movable collimators and 12 fixed masks will compose the new tertiary collimation system in operation for Run4.

(3) Insertion of a new collimation system in the dispersion suppressor (DS) regions around IR2, in a newly designed connection cryostat (installed in LS2). The insertion of the DS collimators in such bypasses placed in

between two 11 T dipoles, around IR7, has been postponed until after LS2 in order to fully assess the need for the collimators in IR7 and the technical maturity of the 11T dipole design. A final decision on the 11T installation for HL-LHC will be taken during Run3.

(4) Insertion of new crystal primary collimators, 1 crystal per plane on each beam, i.e. four crystals with their goniometer, positioning and control systems, to ensure good collimation cleaning for heavy-ion operation. The installation will start before the end of LS2 and will be completed during Run3. See specific section on new equipment baseline.

3.4. *Collider-Experiments interface*

The interfaces between collider and experimental detectors need a change because a smaller β^* entails a large beam size at the entrance in the detector region, so the TAS absorber needs to be made larger and upgraded with the new TAXS. The neutral absorber in the matching sections of IR1 and IR5 will be replaced, too, with a new one called TAXN. A new one, called TANB, that is necessary in IR8 to cope with the increased luminosity of the LHCb experiment has already been installed in summer 2019, representing the first HL-LHC equipment installed in the LHC tunnel! The new TANB absorber is shown in Figure 14.

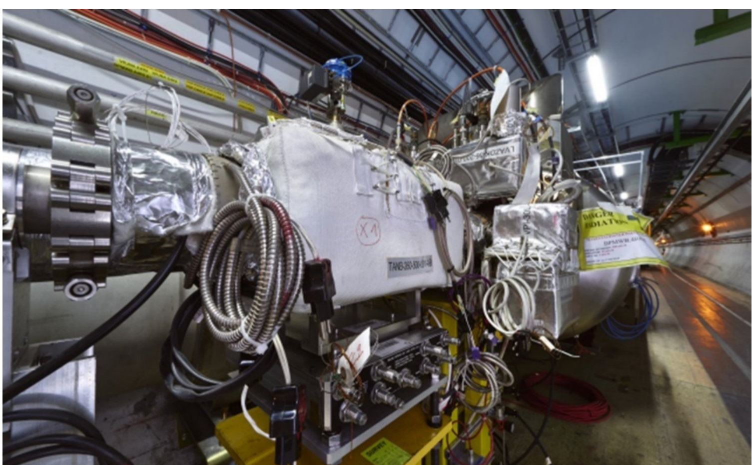

Fig. 14. The TANB absorber.

With the change of the TAXS and of the iron shielding around IP1 and IP5, we profit from the reorganisation of the VAX region, the zone dedicated to the vacuum equipment at the interface between the machine beam pipe and the experimental beam pipe. It is a packed zone with valves, actuators, interlocks and control boards, with very limited accessibility and in high radiation environment. It will be reorganized and rationalized via use of remote-control actuators that allow fully robotic controlled interventions, see Figure 15.

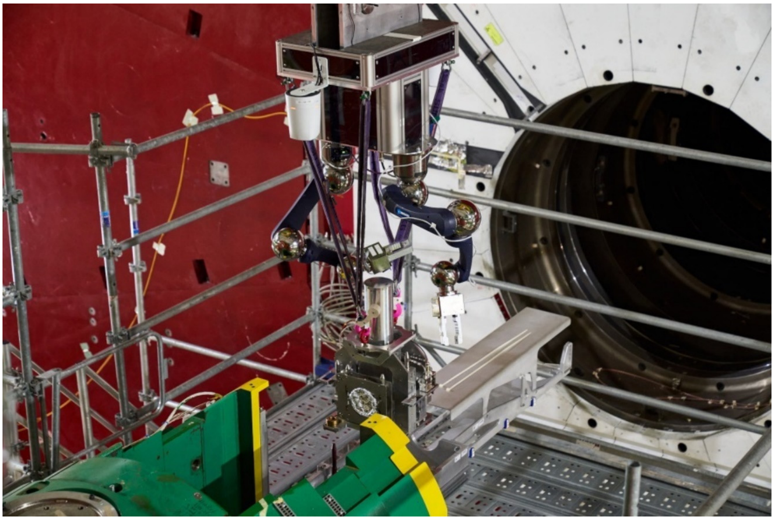

Fig. 15. The CERN CRANEbot handles a VAX module in the CMS cavern.

3.5. *Cryogenics*

The main cryogenic modifications are, of course, at P1 and P5. In each of these points a new 1.9 K cryo-plant, with the same power as the existing LHC cryo-plants (18 kW@4.2 K with 1.8 kW@1.9K cryo-power), will be installed in LS3, to face the increase of heat deposited at cryogenic temperature in the magnet cold mass by the high luminosity regime. The cryo-lines that supply helium to the magnets will be considerably modified and will be separated from the ones of the arc, which will greatly increase the flexibility for operation (a warm-up in the triplet region will not force warming-up the continuous cryostat of the 3 km long sector). The new cryo-line will start from the Q4-CC interface and will extend until Q1 of the IT assembly.

In addition, an upgrade of the existing cryogenic plant in P4 is under way to increase the cooling capacity of the Sector 3-4. Once the upgrades of the cryogenic systems are completed, the Sector 3-4 will become the weakest cryogenic sector after sector 4-5 will be reinforced by the new cryogenic system in P5. The upgrades are already being implemented since LS2 but will be completed only during LS3.

3.6. *Vacuum*

Apart the obvious changes of the vacuum system entailed by the new magnet layout in IR1 and IR5, it is worth underlining a few modifications of the vacuum system as new technological breakthroughs.

(1) The beam screen in the IT triplet is of a new design: octagonal in shape, it is suitable for vertical and horizontal beam crossing at the same time. The beam screen supports a heavy shielding in tungsten alloy (INERMET), of thickness varying between 16 mm (for Q1) and 6 mm (for Q2a/b and Q3), to better protect the 1.9 K superconducting coils from the radiation debris. The HL-LHC beam screen works at 60-90 K, a carefully studied temperature range to avoid desorption gas instability

Fig. 16. A beam screen at the cryolab.

while maximizing by a factor five the gain in efficiency for the power removal when compared to the LHC beam screen in the arcs, that works between 10 and 20 K. Figure 16 shows the new beam screen inserted into a cold bore.

(2) To eliminate the e-cloud effect, all new beam screens will be coated with amorphous carbon (actually carbon nanostructured particulate, deposited via sputtering, that reduce the secondary electron yield SEY < 1. Tested already in a few SPS magnets at room temperature, this a-c coating will be used on a cryogenic surface for the first time. The possibility of using an alternative technique called LESS (laser engineered structured surface) is still being studied. In this case the reduction of the SEY is obtained by "scratching" the surface via a green light power laser. While very attractive, since it does not require to be performed in vacuum like the a-c sputtering process, this technique is not yet fully validated for accelerators (possible issues include high wall impedance, possible powder residuum, etc…). A-C coating will also be retrofitted in the IR8 and IR5 triplet regions. In that case, the only choice is sputtering "onsite" during LS3. In LS2 we anticipate, however, some coating of the beam screens, namely Q5L8, in order to validate the procedure and gain experience with the in-situ application technique in advance with minimal risk.

3.7. *Beam injection and beam dumping systems*

The increased beam intensity in HL-LHC poses great challenges to the beam injection and dumping systems. The need to upgrade these systems even in advance to the full HL-LHC deployment has been evident since Run1. The main upgrades foreseen for the injection and extraction/dumping systems are the following:

(1) Injection kicker MKI has already suffered beam-induced heating, electrical flashovers, beam losses and electron cloud related vacuum pressure rise during LHC operation. Cr_2O_3 coated alumina chambers, an upgraded beam screen with active cooling of the ferrite rings are the main upgrades of the so called "MKI cool" for HL-LHC.

(2) A novel design of the main injection absorber, called TDIS, has been designed for HL-LHC and already installed in LS2 to cope with beam above nominal intensities in Run3. TDIS is segmented (the S of the

name), into three shorter absorbers (∼1.6 m each) accommodated in separate tanks. The two upstream modules will accommodate low-Z graphite absorber blocks, to increase robustness, while the third one hosts higher-Z absorber materials for improved absorption efficiency. Figure 17 shows the TDIS being lowered into the LHC tunnel at Point 1.

(3) The septa protection absorber (TCDS) will be modified to withstand an asynchronous dump with HL-LHC beam. Solutions with different absorbing material or with extra absorber are possible.

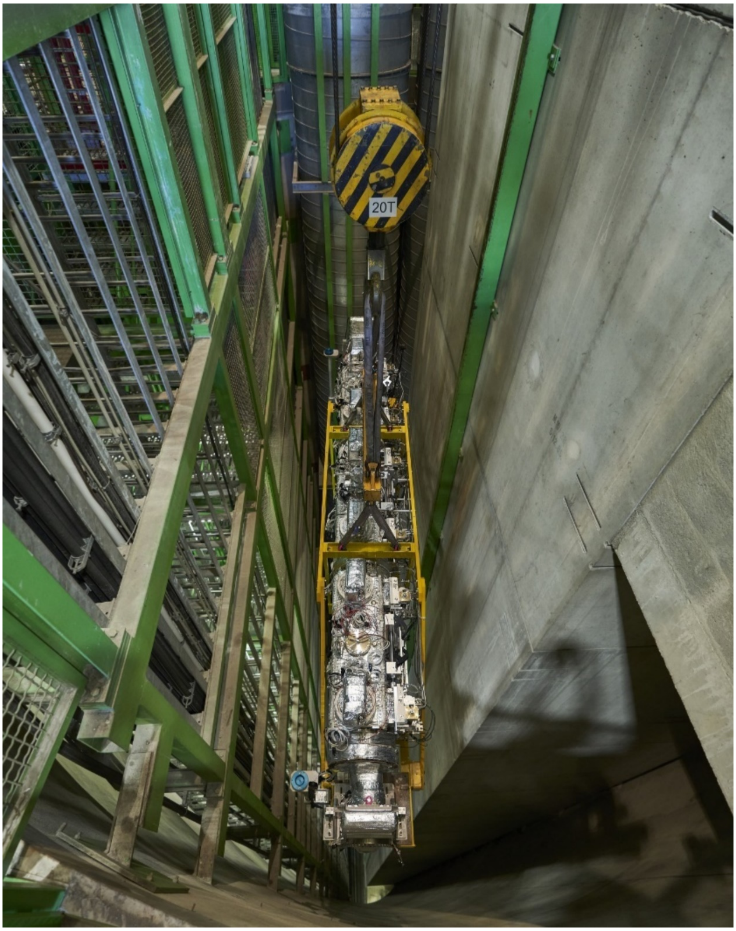

Fig. 17. TDIS lowered into the tunnel at Point 1.

(4) The HV generators of both MKD and MKB (dumping and dilution kickers, respectively) need to be improved in reliability to reduce failure risk and reaction time.
(5) An expected failure mode to the dilution kickers MKB, identified during Run2, could have a catastrophic consequence on the beam dump final absorber (TDE) if happening with the full HL-LHC beam. TDE itself has already shown various weaknesses and is unsuitable for safe operation for HL-LHC (and for the ultimate LHC beam, actually). Therefore, the project is preparing complete re-design of the TDE, which still requires further studies and investigations that are currently underway and prepares the option of a partial upgrade of the MKB system by adding an additional horizontal MKB kicker magnet.

3.8. *Beam instrumentation*

The HL-LHC operation modes with luminosity levelling and tighter control on the acceptable beam halo losses also imply improvements in the beam instrumentation for the HL-LHC exploitation era. The HL-LHC project therefore features the following novel diagnostic tools:

- Radiation hard Beam Position Monitor (BPM) designs for the new IT regions, see Figure 18;

Fig. 18. BPM prototype (body and insert) for the new IT regions.

- 3-dimensional bunch imaging from novel vertex;
- Laser Interferometer Beam Position Monitors for accurate beam position controls near the Crab Cavities.

In addition, the project studied and developed in preparation of future upgrade options a beam halo diagnostics based on Coronagraph technology and Gas Curtain beam profile monitors for measuring the beam overlap of the electron beam of a Hollow Electron Lens (HEL) and the circulating proton beam.

3.9. *Beam control*

In order to cope with the expected larger data volumes and harder radiation environments in the LHC tunnel, the HL-LHC includes a dedicated Controls Technologies work package, that looks after the development of modular and more radiation hard controls electronics and data distribution.

3.10. *Full remote alignment*

During the 2016 re-scoping exercise of the HL-LHC project, it was decided to de-scope the very large aperture MQYY quadrupole magnets, Q4 and Q5 in the high luminosity insertion regions, from the project baseline. The implied reduction in mechanical aperture was compensated by the introduction of a Fully Remote Alignment System (FRAS) that minimizes the radiation exposure of the survey team and thus allows more frequent alignment exercises during a given operation year. The system comprises of special support feet with remote controlled interfaces for adjustments and upgrades in the online survey monitors along the long straight sections in IR1 and IR5.

3.11. *Civil engineering and technical infrastructure*

To host all the new technical services and ancillaries for the new HL-LHC equipment (like power converters, new cryo-plant, cc amplifiers, etc…), the project needed to create new underground areas and surface buildings.

HL-LHC creates significant new infrastructures in LHC P1 (ATLAS) and P5 (CMS). They consist in each point of (see Figures 19 and 20):

- A large shaft of 9 m diameter, 65 m deep.

Fig. 19. Aerial view of the HL-LHC work site at Point 1.

Fig. 20. HL-LHC underground cavern at Point 5.

- New underground caverns and main technical galleries, URs, more than 300 m long, located next to the existing long straight sections of the LHC and located approximately 8 m higher than the existing tunnel. The main UR service tunnel has a distance of approximately 30 m from the existing LHC tunnel.
- Four new, smaller galleries (2 per Interaction Point) connecting the new HL-LHC cavern and galleries to the LHC tunnel. In total the new underground volume is 40,000 m^3 in P1 and P5, each.
- Five new buildings for a surface of 6000 m^2 in a new dedicated area, of about 20,000 m^2.

Most of the new technical equipment will be hosted in the new underground structures which extend in total to about 1 km in length: the two new large (18 kW@4.2K – 2 kW@1.9K) helium refrigerators, electrical power converters with the magnet protection units, the cold powering system, the power amplifier for the SRF CC and all service equipment.

The contracts for the main construction were signed with two consortia (one for each point) in March 2018. The ground-breaking ceremony took place on 15 June 2018 in the presence of CERN Council delegates and local authorities. Construction of the shafts finished almost on time in 2018 and the cavern construction, underground excavation and lining could be finished almost on schedule, well before the LHC resumed operation after LS2 in 2022 (see Figure 1). To assure completion of HL-LHC excavation before beam commissioning for Run3 was the main goal of the "new plan" of HL civil engineering, devised in 2015, when it was clear that vibrations could have hampered LHC luminosity. This is "per se" a great achievement. A second great achievement is the technical success of the works, without serious shortfalls and extra-cost (discounting of course the ones related to the unpredictable Covid-19 emergency). The surface construction works are also proceeded very well, with completion of all buildings by 2023 in-spite of the Covid-19 related delays.

3.12. *Electrical wires for beam-beam compensation: a last option for long-term HL-LHC consolidation*

The long-range beam-beam interactions, which the LHC bunches experience in the long straight section at the unwanted parasitic beam encounters, can be compensated with electrical wires, placed at well-chosen locations and at suitable distances from the circulating beams. While not being part of the HL-LHC baseline, such wires could offer a perspective for future performance improvements in the LHC and the HL-LHC project supports therefore the R&D activity for these devises within its baseline scope. In particular, the HL-LHC project has financed the construction and installation of 4 such devices (electrical wires impeded in the jaws of collimators) next to the experimental insertions at P1 and P5. The installation has been completed during LS1 and the arrangement has been further optimized during LS2 so that further operational experience and understanding can be gained during the upcoming LHC Run3 operation.

4. Performance, Plan and Cost

4.1. *Performance*

The performance of the HL-LHC, both in terms of peak and integrated luminosity, is reported in the plot of Figure 21. The plot assumes that the days for proton luminosity are increased after LS4 due to end of the ion program and, after LS5, for a decrease in MD (machine development) allocated time and in the numbers of technical stops.

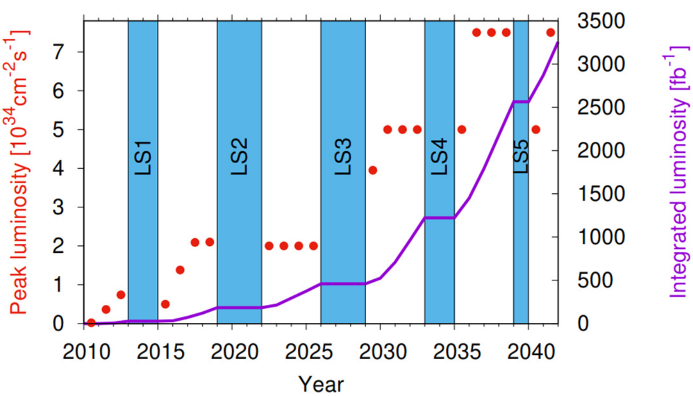

Fig. 21. Peak luminosity (red dots) and integrated luminosity (purple line) vs. time. With the hypothesis of pushing towards ultimate performance (7.5×10^{34}) after LS4, the goal of 3000 fb^{-1} can be reached by 2041, shortly after LS5, while the ultimate target of 4000 fb^{-1} would require a longer Run6 period that extends beyond 2041.

4.2. *Time plan: main milestones*

The global HL-LHC time plan is illustrated in Figure 1.

The plan is based on the following main technical milestones:

- 2014: Preliminary Design Report (PDR) - achieved
- 2015: End of Design Phase, issue of the first version of Technical Design Report (TDR) - achieved
- 2016: Re-baseline to face C.E. extra-cost. Issue of TDR_v0.1 with re-baseline integrated.
- 2017: Test main hardware: only partially achieved with the few outstanding tests planned for 2023.
- 2018: Test of Crab Cavity prototype in SPS (achieved) and first long Nb_3Sn prototype (achieved)
- 2019-2021: LS2 - DS collimators in P2 (ions). Low-Z collimators. Issue of TDR_v1.0 for construction: achieved
- 2019-2021: Construction and test of Magnet prototypes: achieved
- 2019-2025: Construction of main equipment for LS3
- 2023-2025: Installation and test of Inner Triplet String
- 2026-2028: LS3 – Main installation and commissioning.

From the managerial point of view the main achieved milestones have been:

- 2010: Set up of the project by CERN as Design Study under the Accelerator and Technical Directorate and submission of the FP7-HiLumi LHC Design Study application to EC with 20 partners.
- 2011: Approval and start of FP7-HiLumi LHC DS
- 2013: LHC luminosity upgrade declared as priority project by the European Strategy for Particle Physics (CERN Council in Brussels May 30); HL-LHC kick-off meeting as construction project in Daresbury (UK) on 11th of November. Insertion of most budget for HL-LHC in the CERN Medium Term Plan (MTP).
- 2015: End of FP7-HiLumi LHC DS; 1st Cost & Schedule Review. Insertion of all budgets of HL-LHC in the MTP with indication for beyond (Long term plan)
- 2016: Approval of the HL-LHC with entire budget until 2026 by CERN Council in June session. HL-LHC as EU landmark in the ESFRI roadmap. 2nd C&S Review.

- 2017-19: Securing most of the in-kind contribution outside CERN MS: (USA-CN, JP, CA). USA branch of the project (US HL-LHC-AUP) gets CD1 and CD2.
- 2018: Adjudication of C.E. main contracts and ground-breaking ceremony (15 June 2018)
- 2019: First HL-LHC equipment installed in the LHC tunnel (TANB in P8).
- 2020: First two IT Quadrupole magnets for Q1 (From USA) successfully tested for operation: CD3 (green light to full construction) for the US-HL-LHC-AUP.
- 2022: First IT Quadrupole magnets for Q2 (from CERN) successfully tested, confirming all design choices for the Q2 design.

4.3. *Cost*

At the time of writing, the Cost-to-Completion of the full HL-LHC project amounts to about 1,040.4 MCHF of material budget, plus ca. 99 MCHF for HL-LHC spare parts under the HL-LHC CONS budget. The total Cost-to-completion includes in-kind contributions from external institutes, for a core value of 93.7 MCHF. The Cost-to-Completion estimate at the time of writing represents ca. 91.4 MCHF more than the initial cost at the end of 2014, as presented at the first Cost & Schedule Review (C&SR) in March 2015. The 91.4 MCHF are split in 66.6 MCHF of real extra-cost, resulting from a rigorous and continuous cost optimization exercise and the inflation hitting all markets in 2022, and 24.8 MCHF of increased scope, i.e., new equipment, partially obtained as in-kind contribution. In addition to the above material budget, about 2200 FTE-y of CERN staff are accounted for the project, corresponding approximately to 470 MCHF of labour cost. The 1,040.4 MCHF include also approximately 82 MCHF of budget for external, associated personnel, which in CERN's budgeting rules is imputed to "material" budget codes.

Table 3 also gives the cost of the HL-LHC consolidation, i.e., the cost of the totality of the items that are not entering directly into construction but are necessary as spares for continued LHC operation beyond Long Shutdown 3, independently of HL-LHC; for example, the replacement of ageing equipment due to radiation damage to electronics. The consolidation cost of 99.0 MCHF is not incorporated in the direct cost of the HL construction project. Together, HL construction and HL consolidation bring the total budget at completion to

1,139.4 MCHF at the time of writing. The budget breakdown is summarized in Table 3, as presented to the 6th Cost and Schedule Review in 2022. For completeness, the evaluation of the overall cost of HL-LHC should include the cost of personnel working for the project in all contributing institutes others than CERN. However, this would require an impractical normalization of the different accounting of personnel cost, overhead policies, and budget structure in each institute – which has not been carried out in detail. Estimating the personnel in-kind budgetary effort as approximately equal to the in-kind material budget contribution yields a personnel contribution of around 440 FTE-y, which at CERN average cost would be approximately equivalent to 95 MCHF.

Table 3. Breakdown of the total Cost-to-Completion of the HL-LHC project, see text for details.

HL-LHC Construction	M CHF
Material (including Money-for-Personnel	1,040.4
CERN Staff (2271 FTE·year)	472.5
Total HL Construction	1448.0
HL-LHC Consolidation	99.0
HL-LHC Grand Total	1611.9

At the C&SR#5 in November 2021, additional costs for an amount of 14.2 MCHF, related to market conditions, covid related extra cost, performance and schedule risk mitigation, as well as added scopes, were presented to the reviewers and endorsed. The budget required to cover these costs has been requested to the management via the Medium-Term Plan 2022-2027. Market conditions after Covid and the Russian attack on Ukraine impacted the overall project budget, requiring the addition of 51.5 MCHF to cover extra costs of two large cryogenic contracts and other tangible cost changes, partially mitigated by descopings from the insourced Russian contribution.

Figure 22 shows the accumulated Planned budget expenditure versus time, together with the Earned Value and Actual Cost of the material budget, as seen in January 2023. Actual Cost also includes all already committed budget. At the time of writing, about 51% of the budget has been spent, while about 53% of the planned work has been executed - or value earned, in the language of Earned Value Management. The Covid-19 crisis introduced a delay estimated to 6.5 months. In 2021, the Long Shutdown 3 was rescheduled to 2026, thus allowing to reabsorb the delay and some performance limitations in a new baseline, which results shifted by14.2-month with respect to the plan approved at the Cost & Schedule review 2019. The baseline PV shown in Figure 22 was presented to C&SR 2022.

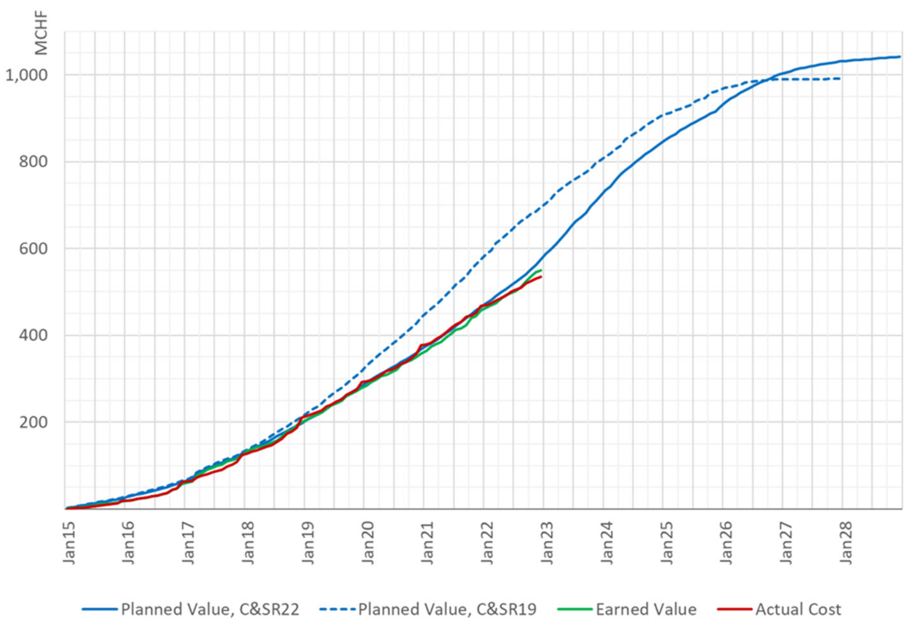

Fig. 22. EVM curves with total cumulative budget, earned value and actual cost, the latter including commitments.

It is worth remembering that according to CERN management rules, the project has been approved without risk contingency, nor managerial reserve, nor price escalation reserve or any other overhead. Therefore, any added cost must be justified and eventually approved by the CERN management, usually after scrutiny and presentation to the Cost & Schedule Review panel. At the C&SR#4 in November 2019, a first comprehensive monetary evaluation of the risk was presented. Based on a detailed risk matrix with vulnerability and impact index assigned to each single item, the extra-cost risk scale was quantified to be in the range of 20-80 MCHF, with the most probable value at 48 MCHF. This led the CERN management to put 50 MCHF of contingency for

HL-LHC in the MTP approved in 2020. At the time of writing, with the additional budget and an increased risk stemming from the volatile market situation, risk is evaluated to 68 MCHF.

5. International Collaboration and Project Governance

5.1. *The international collaboration*

5.1.1. *The initial R&D and design study*

The contribution of the international collaboration for the HL-LHC is even more critical than for LHC. The project heavily relied on the US-DOE-Conductor Development Program, launched in 1998, which was instrumental for improving Nb_3Sn to accelerator quality [18]. The other US-DOE program, LARP (LHC Accelerator Research Program), has been fundamental for HL-LHC: the fifteen year-long LARP program was very beneficial for the IT Quadrupole R&D, as well as for other equipment (e.g., Crab cavities) and studies for the upgrade. The two US programs helped to bolster the credibility of the project when it was launched in 2010. At the time, CERN was just starting Nb_3Sn R&D, and the LARP magnet program provided the necessary proof-of-principle of Nb_3Sn magnet technology.

The EC-FP7 Design Study HiLumi LHC was allowed in 2011 to federate several European Laboratories for the initial studies, as well as KEK-Japan and BINP-Russia. It is worth noticing that HiLumi LHC is the nickname to indicate the part of HL-LHC under the FP7 umbrella (six of the 18 work packages: management and technical coordination, optics and beam performance, magnets, crab cavity, collimators, cold powering) even if in practice has become a popular name to indicate the full project.

Figure 23 shows a summary of all R&D International programs that have supported the LHC upgrade, with the various parallel branches converging to the final HL-LHC target.

Before the set-up of the HL-LHC project, the US-LARP and Japan-KEK collaborations were monitored via bilateral "good-will" agreements. A formal FP7-HiLumi Design Study consortium was implemented during the period 2011-2015, with a Collaboration Board and the governing rules of EC funded programs.

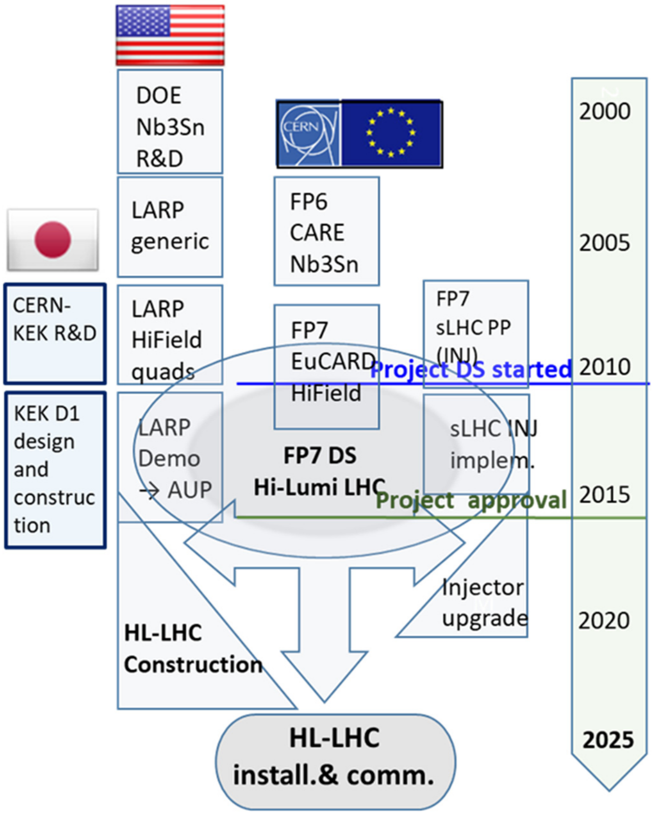

Fig. 23. The International Collaboration set up for the study and various programs toward the High Luminosity LHC.

5.1.2. *Present structure of the international collaborations, HL-LHC MoU and in-kind contributions*

Following the first approval of 2013 and with accelerated pace after the final full approval of 2016, various institutes have joined the project to contribute in-kind. The end of the FP7-HiLumi Consortium, and especially the start of the new construction phase, has required a revision of the governance of the international collaboration.

The HL-LHC Collaboration Board, HLCB, is composed by one member from each Institution that has signed the High Luminosity LHC Memorandum of Understanding (HLMoU). The HLCB membership is possible at two different levels. Full members of the HLCB are, besides CERN, all institutions providing equipment as in-kind contributions (regardless of their value). Institutes participating in the project with regards to design, studies and other types of support not entailing a cost of hardware, i.e., not covering items in the HL-LHC material budget (CORE value in the language of LHC experiments), are observer members of the HLCB. Only full members have a voting right. However, given the nature of consultant body, supervising all external contributions and advising CERN management on the trend of the project, the

Country	Institutions	Contributions	Logos
	INFN Milano - LASA	High-order orbit corrector magnets	INFN Istituto Nazionale di Fisica Nucleare
	INFN Genoa	Separation dipole D2 magnets	
	INFN Ferrara	Crystals	
	CIEMAT	MCBXF nested orbit corrector magnets	Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
	Uppsala University	Cold testing of superconducting orbit corrector magnets and crab cavities DFHM and DFHX cold boxes	UPPSALA UNIVERSITET
	Cockcroft Institute – ASTeC & Lancaster University	DQW crab cavities cryostats	MANCHESTER 1824 The University of Manchester; The Cockcroft Institute of Accelerator Science and Technology; UK Research and Innovation; Lancaster University
	Royal Holloway University & University of Oxford	Beam Instrumentation EO-BPM	MANCHESTER 1824 The University of Manchester; ROYAL HOLLOWAY UNIVERSITY OF LONDON; JAI John Adams Institute for Accelerator Science; UNIVERSITY OF OXFORD
	University of Liverpool	Beam-gas curtain	MANCHESTER 1824 The University of Manchester; UNIVERSITY OF LIVERPOOL
	University of Manchester & University of Dundee	Laser Engineered Surface Structures (LESS)	MANCHESTER 1824 The University of Manchester; University of Dundee
	University of Southampton	DFM and DFX cold boxes	MANCHESTER 1824 The University of Manchester; UNIVERSITY OF Southampton
	PAEC	ATLAS JTT plug 1 shielding	

Fig. 24a. Table of collaborators with in-kind contributions from CERN Member States and Associate Members.

Country	Institutions	Contributions	Logos
	TRIUMF	RFD crab cavities cryostats	TRIUMF
	IHEP CAS	MCBRD orbit corrector magnets	Institute of High Energy Physics Chinese Academy of Sciences
	KEK	Separation dipole D1 cold masses	
	BNL	Nb3Sn low-beta triplet quadrupoles Q1/Q3	U.S. Department of Energy, Office of Science; Brookhaven National Laboratory
	FNAL (leader)	Nb3Sn low-beta triplet quadrupoles Q1/Q3	Fermilab
	LBNL	RFD dressed crab cavities	Berkeley Lab
	SLAC	RFD dressed crab cavities	SLAC National Accelerator Laboratory

Fig. 24b. Table of Collaborators outside CERN Member States with in-kind contributions.

HLCB statements are approved by consensus without voting. The list of countries and Institutions with full memberships of the HLCB is reported in Figure 24a for countries that are CERN member states, and in Figure 24b for Countries that are non-member states (NMS). The mechanism of accounting for in-kind contributions is different in both cases. When an Institute picks up an equipment for in-kind contribution, its value of the corresponding CERN Material budget value is taken as reference to determine the value of the in-kind contribution to the project (like in the LHC experiments, where it is called CORE value). However, for Institutions of a member state, CERN agrees to pay, either in cash or in material supply, half of the value: the in-kind contribution value is then half of the CERN material budget figure. This is done in order to encourage in-kind contributions from member-states, since these they are already supporting CERN via their annual contribution. This way, a considerable number of additional contributions to HL-LHC, beyond the standard budget contribution of the member states to CERN, has been collected. In EU countries, the in-kind contributions amount to a value of ca. 13 MCHF, i.e., European Institutes are directly responsible for manufacturing equipment worth 26 MCHF in the HL-LHC Cost to Completion budget. The total value of all in-kind contributions amounts to ca. 93.7 MCHF in the HL-LHC Cost to Completion budget. This is big success for a CERN-based accelerator. It is also worth considering that in-kind contributions for HL-LHC are important not only for their "CORE" value. The staff deployed by the collaborating institute is indeed a critical and necessary addition to the CERN staff for the project, both numerically, as well as in terms of quality and skill terms.

5.2. *Project structure and governance*

The HL-LHC project is organised in four main offices:

- The Budget and Schedule Office that looks after the overall budget and schedule
- The Collaborations Office that looks after the external collaborations
- The Procurement, Baseline Documentation and Quality Assurance and Risk Office
- The Integration and Installation Office.

In addition to these four main offices, the project features a Communication and Outreach office and a Safety office. Figure 25 illustrates the HL-LHC Project Office structure and illustrates the main links to CERN groups and entities.

The technical work is organised into 19 work packages (WP) that are listed in Figure 26. The first six work packages, WP1 to WP6a, were part of the FP7

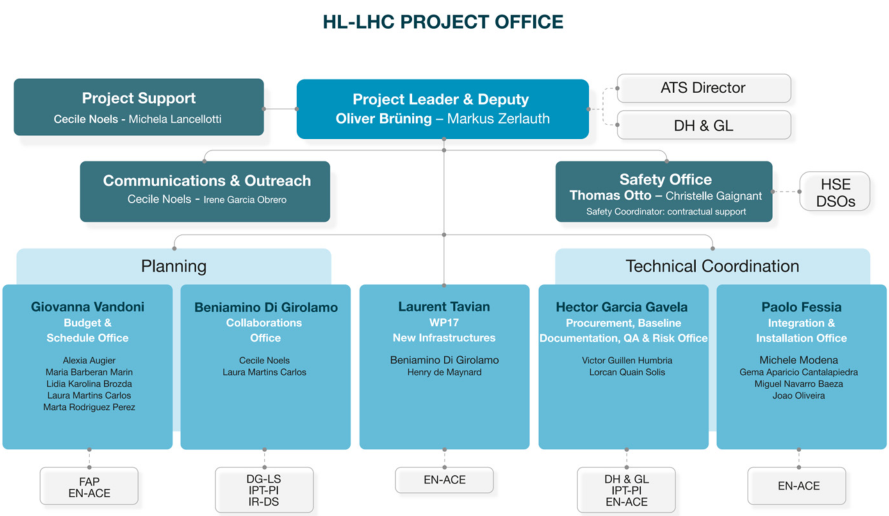

Fig. 25. The HL-LHC Project Office.

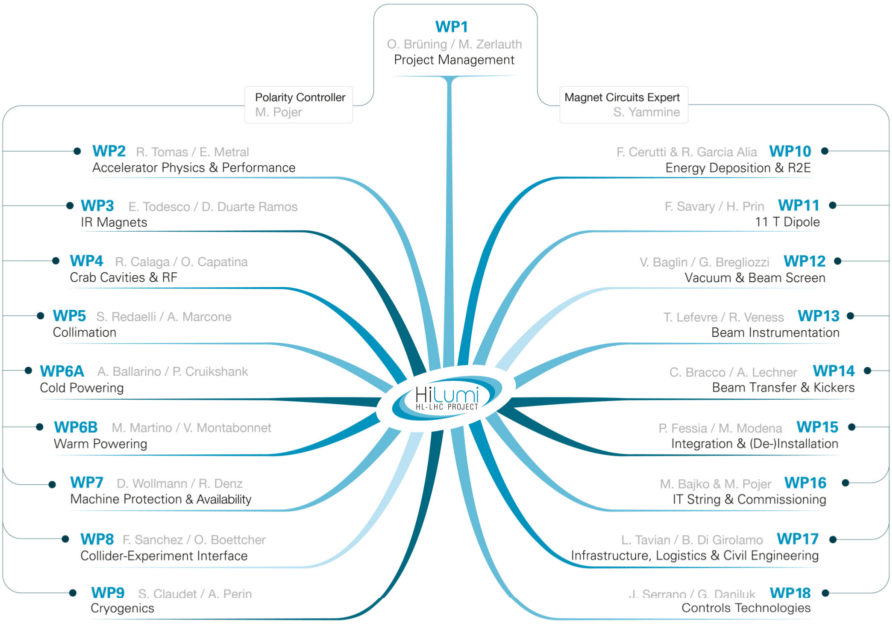

Fig. 26. The HL-LHC work package structure.

Design Study. A 'Polarity Controller' and a 'Magnet Circuits Expert' ensure the integrity and conformity of the final magnet powering circuits.

Work package 17 has a special role in the project office and is the only HL-LHC work package that is explicitly represented in the HL-LHC Project Office. WP17 looks after the civil engineering work and the construction of the new technical infrastructures for the HL-LHC. It has a direct link with the CERN SCE department that is following the civil engineering contracts for the HL-LHC project.

The Budget & Schedule Office and the Collaborations Office use the Project Steering Meetings (PSM) to interface and monitor the budget and schedule progress of each work package and to establish the link with the associated Departments and Groups at CERN. The regularity of the meetings varies between work packages. But overall, the project features on average ca. two PSM per week. The Procurement, Baseline Documentation and QA & Risk Office and the Integration & Installation Office use the Technical Coordination Committee (TCC) to coordinate their work across all the HL-LHC work packages and to disseminate the technical information to the CERN Departments and Groups. The project features on average one TCC meeting every two weeks.

In addition to the PSM and TCC meetings, the Project Office interfaces with the upgrade coordinators of the experiments through the Coordination Group and with the SCE Department of CERN through a dedicated SCE Steering committee to follow-up on HL-LHC related civil engineering work.

The HL-LHC project reports to the Director of the Accelerators and Technology Sector and meets regularly with the spokespersons of the experiments and the CERN management, Directors and department heads, through the HL-LHC Executive Committee that is chaired by the ATS Director. The CERN management regularly consults the CERN Machine Advisory Committee (CMAC), at least once per year, and organizes an external Cost & Schedule Review approximately every 12 months in order to evaluate the project progress and to generate the reporting to the CERN Council. Figure 27 illustrates this line of reporting with the CERN management and lists the interfaces of the HL-LHC management with key groups and bodies at CERN [light boxes on the right]. The HL-LHC project governs the international collaborations through dedicated Steering Committees for each collaboration

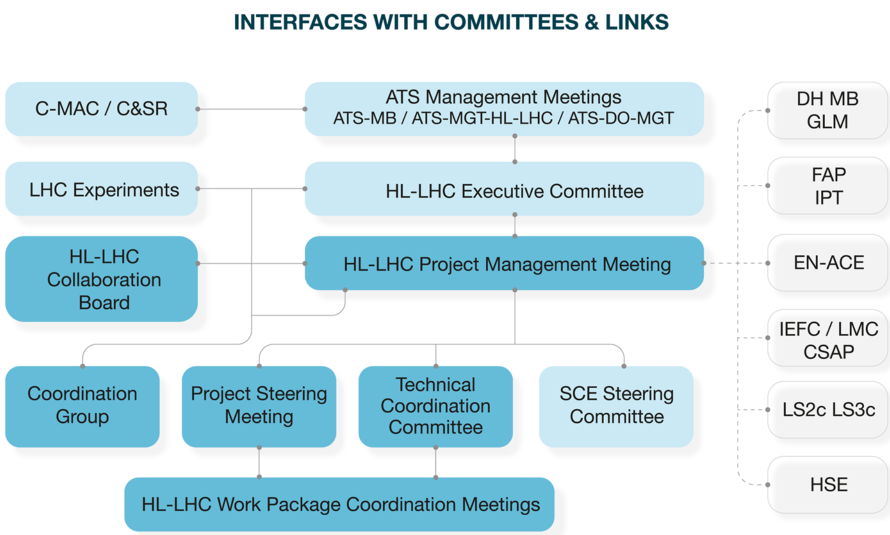

Fig. 27. The HL-LHC interfaces with committees and other CERN units.

and through a Collaboration Board, that involves one representative from each collaboration and meets on an annual basis.

Figure 27 summarizes the main interfaces of the HL-LHC project with Committees and lists links to the key CERN structures.

References

1. European Strategy for Particle Physics, adopted by the CERN Council at a special session at ministerial level in Lisbon in 2006. http://cern.ch/council/en/EuropeanStrategy/ESParticlePhysics.html.
2. European Strategy Forum for Research Infrastructures, ESFRI, http://ec.europa.eu/research/esfri.
3. The European Strategy for Particle Physics Update 2013, CERN-Council-S/106, adopted at a special session in the Brussels on 30 May 2013. http://cern.ch/council/en/EuropeanStrategy/ESParticlePhysics.html.
4. Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context, in http://science.energy.gov/hep/hepap/reports/.
5. Lucio Rossi, LHC Upgrade Plans: Options and Strategy, *Proceedings of IPAC2011*, San Sebastián, Spain, 01/09/2011, pp. 908-912.
6. Lucio Rossi and Oliver Brüning, High Luminosity Large Hadron Collider - A description for the European Strategy Preparatory Group, CERN-ATS-2012-236.
7. The High-Luminosity LHC (HL-LHC) Project, CERN/SPC/1068, CERN/FC/6014, CERN/3255, 30 May 2016.
8. Commission presents its evaluation of the 7th Framework Programme for Research, 7th Framework Programme for Research, MEMO/16/146, 25 January 2016.
9. EUROPEAN COMMISSION – 7th Framework Programme for Research – EVALUATION SUMMARY REPORT: HiLumi LHC_284404.
10. ECFA High Luminosity LHC Experiments Workshops – 2013 and 2014, https://indico.cern.ch/event/252045/ and https://indico.cern.ch/event/315626/.
11. H. Damerau et al., Upgrade Plans for the LHC Injector Complex, *Proceedings of IPAC2012*, New Orleans, Louisiana, USA, pp. 1010-1014.
12. H. Damerau et al., RF Manipulations for Higher Brightness LHC-Type Beams, CERN, Geneva, Switzerland, Rep. CERN-ACC-2013-0210, 2013, https://cds.cern.ch/record/1595719.
13. J. Strait et al., Towards a New LHC Interaction Region Design for a Luminosity Upgrade, *Proceedings of the 2003 Particle Accelerator Conference (PAC2003)*, Portland, OR, USA, 12-16 May 2003, Vol. 1, pp. 42-44; also available as: CERN-LHC-Project Report 643.
14. R. van Welderen, CERN, private communication.
15. R. M. Scanlan, *IEEE Trans. Appl. Supercond. 11*, 2150 (2001).

16. S. Farthoukh et al., LHC Configuration and Operational Scenario for Run 3, CERN-ACC-2021-0007, 12 November 2021.
17. High Luminosity Large Hadron Collider (HL-LHC): Technical design report, I. Béjar Alonso I. Béjar Alonso, O. Brüning, P. Fessia, M. Lamont, L. Rossi, L. Tavian, M. Zerlauth, *CERN Yellow Reports: Monographs*, CERN-2020-010, CERN, Geneva, 2020, 10.23731/CYRM-2020-0010.
18. N. Mokhov, I. Rakhno, J. Kerby and J. Strait, Protecting LHC IP1/IP5 Components Against Radiation Resulting from Colliding Beam Interactions, CERN-LHC-Project-Report-633; FERMILAB-FN-0732, April 2003.