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PROGRESS WITH THE HIGH LUMINOSITY LHC PROJECT AT CERN*

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Abstract

The High Luminosity LHC (HL-LHC) project aims at upgrading the LHC by increasing the peak luminosity, to allow collecting 3000 fb^{-1} for ATLAS and CMS experiments, each, which is ten times more than the initial LHC expectations. The upgrade is based on multiple factors, like: doubling the beam current, operation in levelling mode, the deploying of a stronger and larger aperture inner quadrupole triplet in the low-beta insertions, thanks to the use of Nb_3Sn superconductor with almost 12 T peak field in the coils. We will make use of compact crab cavities (a novelty for hadrons) to allow almost head-on collisions despite the larger crossing angle. A collimator insertion in the dispersion suppressor region to handle the losses in the cold part of the machine is possible thanks to the use of a few 11 T dipoles based on Nb_3Sn technology. We also aim at reducing drastically the impedance contribution of collimators by utilizing new materials and coating techniques. Many other new technologies are developed for HL-LHC, like new superconducting links of 100 kA: HL-LHC is important as a technology turning point for future post-LHC HEP colliders as it is for enhancing the LHC Physics reach.

INTRODUCTION

The LHC complex, the collider with its injectors and experiments, is working very well. After the discovery of the Higgs boson in 2012, based on 5 fb^{-1} at 3.5+3.5 TeV and 5 fb^{-1} at 4+4 TeV collected in each of the two high luminosity experiment (ATLAS in the LHC P1 and CMS in LHC P5), the LHC ran successfully for further four years (2015-18). It has reached the nominal luminosity of $L_0=10^{34}$ $cm^{-2}s^{-1}$ in 2016 and it has even doubled that figure in 2018, accumulating some 190 fb^{-1}, almost all at 6.5+6.5 TeV beam energy. LHC integrated luminosity is already above 60% of the initially planned 300 fb^{-1} (at 7+7 TeV). In order to maximize the physics reach of the LHC, i.e. return for investment for the ten thousands users of the LHC, in 2010 CERN has set up the High Luminosity LHC project (HL-LHC), [1,2], when LHC was just starting high energy collision at few 10^{32} $cm^{-2}s^{-1}$ luminosity, with the following goals:

reaching a luminosity of $L_{lev}=5\times10^{34}$ $cm^{-2}s^{-1}$, working in a levelling mode, to reach an integrated luminosity of 250 fb^{-1}/year;

reaching a total integrated luminosity of 3000 fb^{-1} in 10 years of operation after upgrade.

These goals are 5 times larger than the nominal design LHC goals in term of peak luminosity L_0 and 10 times in term of integrated luminosity. The reason of the larger gain in integrated luminosity than in peak one, is the operation in levelling mode. Actually the HL-LHC parameters would allow to reach $17L_0$, however we limit the initial luminosity levelling it for long time as shown in Fig. 1. Limiting the maximum luminosity entails a moderate loss of about 20% in integrated luminosity but it has the big advantage to overcome the limitation of heat deposition in the superconducting magnets near the collision points (limitation in the coils and in the cryogenics) and limitation in the detector data taking, i.e. the collision pile-up, a key feature for experiments to improve the quality of the physics analysis.

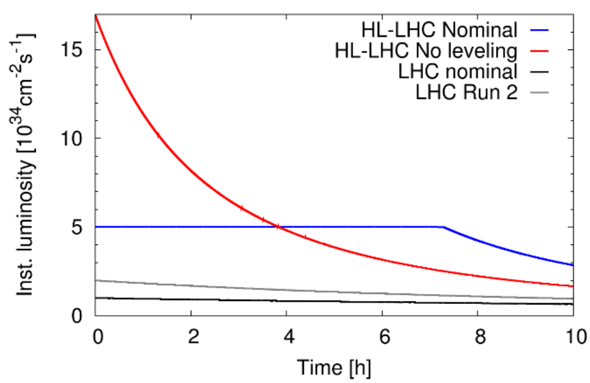

Figure 1: Luminosity evolution along a HL-LHC fill in case of no-levelling (red) and levelling mode (blue). The no-levelling standard mode of the LHC with nominal design parameters and with Run 2 ones are shown, too.

The timing of the upgrade is given by radiation damage to the inner tracker of the LHC experiments ATLAS and CMS and in the LHC inner triplet (IT) magnets (quadrupoles and orbit correctors) as well as by the reduction in physics interest once the increase in luminosity stagnates, requiring more and more running time to half the statistical errors. Fig. 2 shows the integrated LHC/HL-LHC programme, with main HL-LHC installation foreseen during LS3 (2024-26).

MAIN INGREDIENTS OF THE UPGRAGE AND PERFORMANCE REACH

The LHC machine is so well optimized that it is difficult to improve it without a serious upgrade of many technical systems. As pointed out first by F. Zimmermann in [3], the integrated luminosity in a levelled operated collider depends strongly on the number of circulating protons (the initial "charge"). However each term counts [for example the emittance and β*] and the fact that performance depends, apart from the total number of protons, on many parameters is also an advantage because the impact on the integrated luminosity of underperformance of a single parameter is limited.

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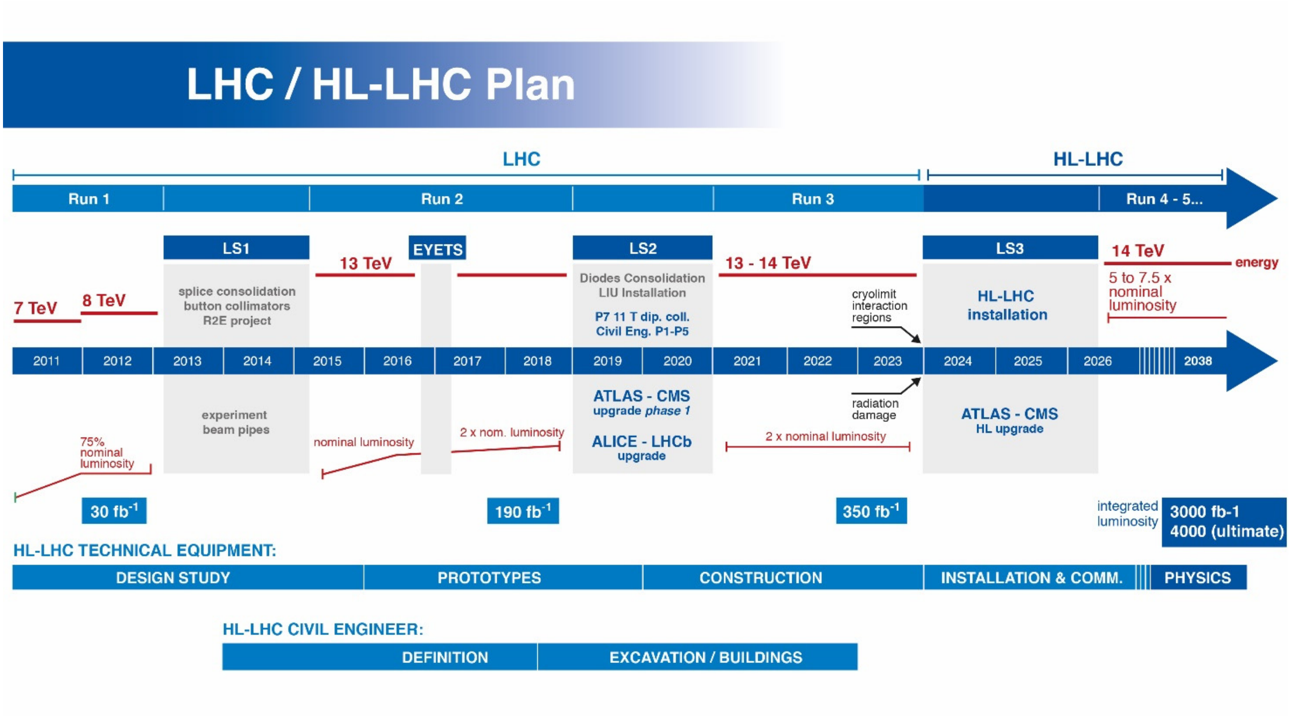

Figure 2: The LHC and HL-LHC time line from HL-LHC design start to the end of physics run.

Luminosity, defined as the number of events per second per unit cross section, for a circular collider with round beams can be expressed in terms of beam parameters as:

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

In the following we describe briefly the main features of the LHC on which we act for upgrading it to the high luminosity configuration.

Beam Current

The beam current will be increased from 0.58 A (LHC nominal design values) to 1.09 A; this means increasing bunch population (numbers of bunches is limited to 2748 by 25 ns minimum bunch spacing) from 1.1 to 2.2×10^{11} protons. The luminosity depends quadratically on bunch population, see above equation. However, in the levelled regime the most important figure of merit, the integrated luminosity has a more complex dependence on bunch population. The LHC Injector Upgrade project [4] has the primarily objective to inject into LHC bunches with 2.3×10^{11} protons and a small normalized emittance of $\varepsilon_n \leq 2.1$ µm. This results in an increase in brightness of more than a factor two with respect to present injector performance. The small emittance contributes directly to the luminosity, see above equation, and indirectly by allowing a smaller crossing angle, i.e. by limiting the effect of the reduction factor R in (1). Of course a major task for the HL-LHC is to deal safely with the high brightness beams, allowing not more than 10-20% degradation during the injection, the acceleration and the squeezing-collision mode. Many new sophisticated studies of beam optics and dynamics have been carried out to overcome LHC beam parameters limitation. The most remarkable are the studies of beam dynamic aperture with beam-beam effects (especially long-range), non-linear optics measurements and corrections and noise effects [5]. A nice summary of the operational scenarios deriving from all beam studies and hardware performance can be found in [6, 7].

Finally, it is worth mentioning that we have defined the "ultimate performance" of the HL-LHC as the goal we intend to reach slowly by using the engineering margin built into the design of each equipment [8]. We think that without unexpected shortfalls we should be able to reach and even pass: L_{ult}=7.5 L_0 and 330-350 fb^{-1}/year. This last figure of course strongly depends on the actual availability and efficiency of the collider. For the moment we count on 50% efficiency, a high level demonstrated in the Run 2.

New ATS Optics

A key element of the upgrade is the deployment of the new optics, called ATS [9], capable of overcoming two fundamental limitation of the LHC design: i) the matching between insertion regions and arcs, and ii) correction of the enormous chromatic aberrations induced by the 20 km β-function in the IT quadrupoles. Both limitation would limit the β* reach to about 30 cm, as original foreseen in the first ideas of the LHC luminosity upgrade [10]. The ATS (achromatic telescopic scheme) utilises a huge beta-beating wave in the arcs neighbouring the high luminosity insertions, IR1 and IR5. The large controlled beam size in the arc allows to boost the effect of the arc sextupoles and to fully correct the large chromatic aberration of the triplet. In this way we can make full use of the larger aperture of the new triplet, and design the upgrade machine for β* of 15 cm (or even smaller if some design margins can be used).

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The ATS has been tested in LHC operation and, together with operation in levelled mode, will boost the LHC Run3 performance. The upgrade starts by making already the present LHC better!

MAIN HARDWARE AND STATUS

Quadrupole Aperture and β Reduction*

A classical route to luminosity increase is to reduce the β* (β-function value at collision point), see for example [11] and [12], by installing larger aperture quadrupole triplet near the collision points (called IT or inner triplet quadrupoles). The IT quadrupoles are the magnets most exposed to radiation debris escaping form collision along the beam pipe, therefore suffering from damage. Indeed in LHC this quadrupoles are safe until a luminosity of 300-400 fb^{-1}, the same limit at which the inner tracker of the high luminosity experiments, ATLAS and CMS, is heavily degraded by radiation damage. Changing the IT quadrupoles (and all other equipment associated) and the inner trackers of the experiments is a major operation requiring a synchronized stop of operations of 2-3 years, see Fig.2.

The new IT quadrupoles have an aperture of 150 mm (vs 70 mm of the present LHC quadrupoles) allowing a reduction of β* by almost a factor four with respect to the LHC nominal value: 15 cm vs. 55 cm. The quadrupoles have a gradient of 132 T/m, with a peak field of about 11.5 T in the superconducting coils. This requires use of Nb_3Sn superconductor, a technology challenge of the upgrade.

The sense of the challenges is given in Fig. 3 where the cross section and main parameters of the LHC IT quadrupoles (MQXA/B) are compared with the HL-LHC one, MQXF. The design has been based on the 15 year-long technology R&D of the US-DOE LARP program [13].

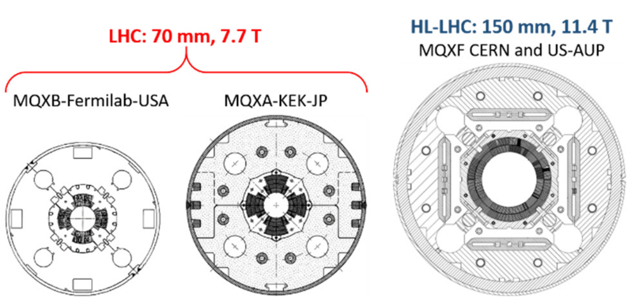

Figure 3: comparison of cross-sections of IT quadrupoles used for LHC and for HL-LHC.

The 4,000 km of high critical current density Nb_3Sn superconducting wire, of the RRP™ type, is under procurement (about 50% delivered and well above specifications).

In total we need 20 IT quadrupoles (including 4 spares). Half are delivered in-kind by the US-DOE branch of the project called HL-LHC AUP, namely the Q1 and Q3 units; the remaining Q2A and Q2B units are responsibility of CERN.

Many other magnets, namely the separation-recombination dipole pair (D1 and D2, in-kind contribution of KEK-Japan and INFN-Italy, respectively), the numerous orbit corrector dipoles (in-kind contributions of CIEMAT-Spain and IHEP-China) and high order correctors magnets (in-kind contribution of INFN-Italy) have to be changed in the insertion regions of P1 and P5 to cope with aperture increase demanded by the smaller β*. In spite being of classical Nb-Ti, each one of it is a breakthrough either because they are pushed at the limit of the technology or because they imply new technologies: superferric design for HO correctors, new mechanical design for the nested orbit correctors and CCT (Canted Cosine Theta) configuration for the recombination dipole orbit correctors.

Crab Cavities

The large crossing angle induced by the very small β* (235 μrad vs 140 of the nominal LHC) push down the reduction factor R of the luminosity formula, form 0.85 for the nominal LHC down to 0.35 in HL-LHC, see Fig.4. To compensate this we have devised the used of compact crab cavities. Placed in the insertion regions about 200 m from the collision point in IR1 and IR5, these SRF cavities working at 400 MHz kick the beams transversally, tilting each bunch around its barycentre in such a way that the two beams collides practically head-on despite the angle of the trajectories, see Fig. 4, where one can notice that the reduction factor is almost fully compensated.

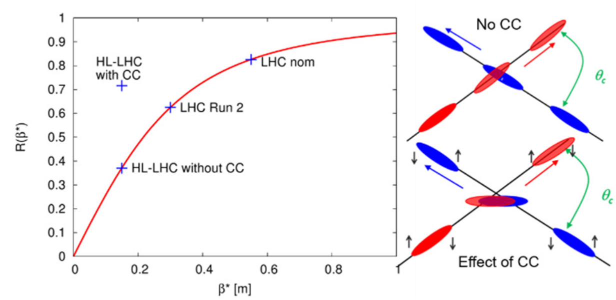

Figure 4: Reduction factor R vs β* and crab cavity (CC) effect.

Despite their apparent big effect on peak luminosity, a factor two, the actual effect of crab cavity on integrated luminosity is limited to 10-20% (for levelling at L=5-7.5×L_0), because the baseline levelling via β* allows to reduce the crossing angle during a fill. However, crab cavities is an important knob to increase operation flexibility.

Two configurations of crab cavities are used in HL-LHC, see Fig. 5: i) Double Quarter Wave (DQW), 8 cavities in 4 cryo modules, for vertical deflection; ii) RF Dipole (RFD), 8 cavities in 4 cryo-modules for horizontal deflection.

After the completion of various proof-of-principle cavity prototypes by US-LARP and Lancaster University (UK), about eight cavity prototypes have been (or are being) manufactured by US-LARP and CERN, with the support of STFC and Univ. of Lancaster (UK). They all meet specifications, and the two DQW cavities, of CERN have been completed as dressed cavity and then assembled in a prototype cryo-module and installed in a newly prepared test facility in the CERN SPS. The cryo-module has been tested on the intense 450 GeV proton beam of SPS during 2018,

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first time of use of a crab cavity in a proton beam. The test has been successful, demonstrating, among other things, the "transparency" to beam. The construction of the cavities has been launched via industrial contracts both by CERN for DQW and by US-HL-AUP for RFD type. The construction of the cryo-module is foreseen by CERN and SFTC (UK) as in-kind for the DQW and by TRIUMF (Canada) for the RFD.

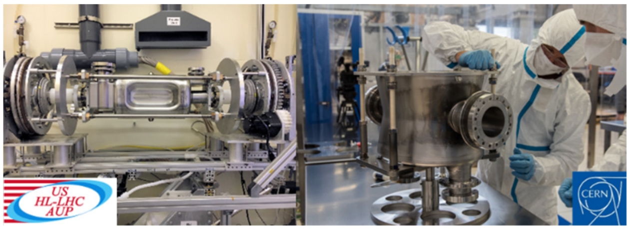

Figure 5: RFD cavity under chemistry at ANL by US-AUP, left, DQW cavity under assembly at CERN, right.

Collimators and Absorbers to Manage High Intensity Beams and Reduce Radiation Hazard

Dealing with beams that are twice as intense as the nominal and even 30% higher than what was supposed to be the ultimate limit of LHC requires many upgrades of the collimation system and of various beam intercepting devices.

- Insertion of a new collimation system in the dispersion suppressor regions around IR7 and IR2. To this aim, only in IR7, a new bypass creating a room temperature region of about 1 m is placed in between two 11 T dipoles (with novel Nb_3Sn technology) whose installation is foresee already in LS2 (2020).
- Upgrade of some 18 collimators (8 during LS2) of secondary type with new jaws, manufactured in molybdenum-graphite composite (MoGR) and then coated with molybdenum, see Fig. 7. The projected impedance reduction is a big step to assure stable beams of such intensity for HL-LHC.
- Upgrade of the tertiary collimator system (12 units) to cope with larger triplet aperture and robustness increase (use of copper-diamond jaws instead of present tungsten jaws) and addition or upgrade of 8 collimators and 12 fixed mask to intercept debris form collision.
- Upgrade of the main protection system for beam injection, called TDIS: it will be segmented and will use two graphite absorber blocks followed by a third module with higher-Z absorber materials (Ti6Al4V and CuCr1Zr) to better absorb and efficiently attenuate the particle showers from the low density upstream blocks. Other modifications are being carried out on the injection kickers, with cooling of the ferrite to avoid passing the Curie temperature.
- The beam dump system is also considered for an important upgrade because both of unexpected failure mode of beam dilution kickers (2018 event) and of a very high temperature (with possible melting) of the final absorber.
- The Collider-Experiment region will be deeply changed to accommodate the new TAXS, the first absorber of the collision debris, that has to increase aperture to allow the smaller β*, and a rearrangement of the vacuum zone that will be rationalized and adapted for remote handling (it is probably the most radioactive zone of the whole LHC).

Cold and Warm Powering and Other Equipment

The new, larger and more numerous, power converters for the insertion region magnets will be placed in a new service gallery along the LHC tunnel, eliminating radiation hazard both to personnel intervening on power converters and to equipment. The gallery will be accessible even during operation. To avoid excessive power dissipation and water cooled cables, the 100 kA feeding the various magnet circuits are carried over 120-150m by superconducting links. To increase operational margins, i.e. temperature margin, and to avoid use of liquid He in the galleries, the link uses about 1000km of MgB_2 superconducting wire, which can operate up to 20 K (25 K being the maximum temperature) requiring only gaseous He. These links will feature also a section of a few meters of HTS cable between the MgB_2 and the 50 K low extremity of the copper current leads. The cable lay-out has been finalized, tested on short pieces and now, a 60 m prototype cable is under way. Recently the first 60 m of the main circuit sub-cable (20 kA) with complete system of current leads and cold boxes has been successfully tested with no quench in non-standard operative conditions, see Fig. 6.

Figure 6: 60 m prototype superconducting link of 20 kA in a flexible cryostat under test in March 2019 at CERN.

A new type of electrical power converter is very important for the upgrade: a Class 0, 2-Quadrants 20 kA-±10V power converter is being developed for powering of the inner triplet. It will improve field stability w.r.t. present triplet and will allow much faster current decrease, a current performance limitation in the LHC.

Many other ingredients are important for the upgrades, for example (but not only): i) new protection system of the magnets; ii) a new beam screen with W-shielding at 60-80 K to intercept much more debris and at higher temperature than in LHC, this limiting the cryogenic power despite the much higher peak luminosity, iii) new beam instrumentation (BPM that are able to distinguish incoming and outgoing beam inside the same beam pipe); iiii) two new large cryo-plants increasing LHC cryo-power by 25%, etc.... We cannot cover all but they are well described in [8, 14].

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CILVIL ENGINEER AND TECHNCAL INFRASTRUCTURE

HL-LHC requires a considerable extension of the technical infrastructure in LHC P1 (ATLAS) and P5 (CMS). It consists in each point of (see Fig. 7):

- A large shaft of 9 m diameter, 65 m deep.
- Underground caverns and main technical galleries, more than 300 m long, along the LHC tunnel at about 30 m distance and 8 m above it.
- Four galleries connecting the HiLumi 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.

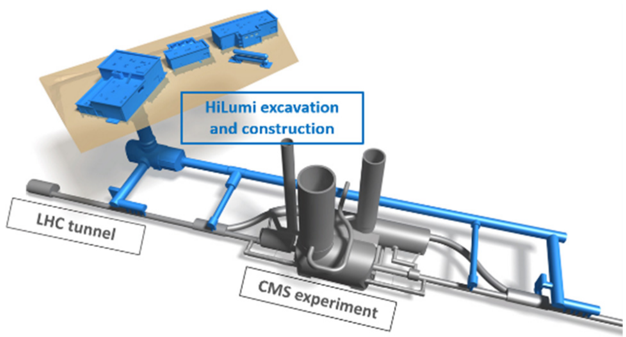

Figure 7: extension of the civil engineering works for HiLumi (in blue) in LHC P5. The same is in LHC P1-ATLAS.

Many technical equipment will be hosted in the about 1 km total length new underground structure: the two new large (18kW@4.2K, 2.5 kW@1.9K) helium refrigerators, electrical power converter with the magnet protections units, the cold powering, the solid state 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 was held on 15 June 2018 at the presence of CERN Council delegates and local authorities. Construction of the shafts finished almost on time in 2018 and the cavern construction is well underway, see Fig. 8, and so far we did not experience any serious issue. Underground excavation works will finish in 2020, well before LHC resumes operation after LS2 (see Fig. 2).

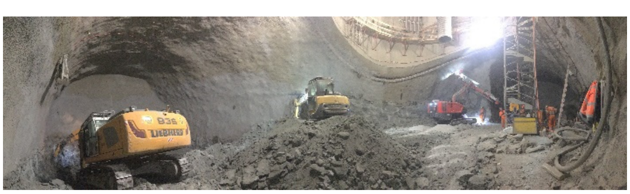

Figure 8: Construction of main cavern for HiLumi in P1. (Picture courtesy of consortium JVMM-Contract T117).

INTERNATIONAL COLLABORATION, COST AND PLANNING

HL-LHC relies since the beginning on a broad International collaboration. The R&D on Nb_3Sn that is so essential for the project started actual in USA, especially via the US-DOE-LARP (Lhc Accelerator R&d Programme), federating four National laboratories, BNL, LBNL, SLAC and Fermilab (managing lab). LARP lasted from 2004 to 2018 when US-DOE set-up a project, US HL-LHC-AUP, in order to provide 10 IT Quadrupoles fully cryostated and 10 dressed Crab Cavities. Also KEK-Japan joined quite early the project and is committed to deliver the cold mass of 6 D1 dipoles, while TRIUMF-Canada is arranging to provide the cryo-module for the US cavities. China is providing 12 orbit corrector magnets of the CCT type and the Russian Federation has just signed the commitment to provide the solid state amplifiers for the CC system and the TAXS/N absorbers, while discussing further contributions, like the electron-lens, Current Leads, Beam dump, etc.

To be noticed the extended in-kind contribution also of CERN member state laboratories and institutions. The main ones are: i) INFN-Italy, providing the magnetic part of 6 D2 dipoles (Genova) and 54 high order corrector magnets (Milano-LASA), ii) CIEMAT-Spain, providing the magnetic part of 16 nested orbit corrector dipoles; iii) the STFC-UK providing four cryo-modules for the DQW cavities and, in conjunction with Univ. of South-Hampton, 5 magnet powering cold boxes; iiii) Uppsala University that is meant to provide further 5 magnet powering cold boxes and to test orbit correctors and CC.

The project budget breakdown is reported in the Table 1. According to CERN rule, the budget does not contain any overheads, contingency, provision and price escalation.

Table 1: Cost of the Project. M=Material, P=Personnel

Description	Cost (MCHF)	Comments
Construction M	951	Incl.~120 in-kinds
Construction P	435	Ca. 2000 FTE-y
TOTAL constr.	1,436	M+P
Consolidation	80	Spares included

The project has about 5 month of non-critical delay with respect to the schedule fixed at end of 2015, mainly due to industrialization of the long Nb_3Sn magnets, both the 11 T and the IT quadrupoles, which is not surprising because it is the most difficult and innovative technology. The time plan will be scrutinized at the 4th Cost& Schedule review next November 2019. At that time a decision if the delay can be absorbed or has to entail a shift of one year in the installation is to be taken. So far we have committed about 40% of the material budget with an extra cost of about 1.5 % on the technical part (mainly magnet system) and further 1.5% for the civil engineering contracts. We target to stay well below the 5% extra-cost on material that can be considered a great success for such an innovative project, approved without any contingency or reserve.

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