# HOW TO IMPLEMENT ALL HL-LHC UPGRADES

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*Abstract*

The luminosity upgrade will require major changes in the LHC machine layout: about 1.2 km of the machine will undergo major renovation or modification. In the paper we will review the list of main equipment foreseen to be replaced or to be added. We will review the upgrade plan that should start already in the Long Shutdown (LS) 2 (with the installation of the first dispersion suppressor 11T dipole – collimator unit, the superconducting link in Pount 7 and the cryo-plant in Point 4), through to the major works in LS3, synchronized with an upgrade of the LHC detectors. Best estimates of the required duration of the various shutdowns will be discussed, and also the main risks and their mitigation.

## INTRODUCTION

The High Luminosity LHC (HL-LHC) Project has been established in autumn 2010 by the CERN Director of Accelerator & Technology, as a new plan for LHC and injector upgrades following the plan change suggested at the Chamonix LHC Performance workshop held on 25-29 January 2010 [1,2]. By summer 2010 the project mission, a design phase detailed plan, the constitution of a world-wide collaboration (20 Institutes) and a global plan for construction and implementation were set up. This allowed writing at the end of 2010 an application to the European Commission to get support as FP7 Design Study, called HiLumi LHC. The application has been successful and the FP7-HiLumi LHC Design Study began on the 1st of November 2011, successfully marking the official start of the design phase.

Another milestone of the project, has been the 30th of May 2013, when the CERN Council in a special session held in Brussels, in presence of EU Commission and CERN Member States officials, adopted the new European Strategy for high energy physics. The HL-LHC was placed as a first priority program in the strategy declaration [3], supporting the LHC upgrade in luminosity by the following statement: ...*Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.* This was exactly the initial scope of HL-LHC project, aiming at increasing the integrated luminosity reach from the initial target of 300 $fb^{-1}$ up to about 3000 $fb^{-1}$, at a rate of 250 $fb^{-1}$/y. This main goal has been complemented with two "conditions": the first one is to limit the pile up at about 140 events/crossing, which means limiting the peak luminosity to $5{\cdot}10^{34}$ $cm^{-2}$ $s^{-1}$. The second condition is subtler: to limit the pile up linear density to about 1 event/mm. Pile up density, mentioned in the second joint HL-LHC and LIU workshop, has emerged as target only recently [4], however a novel solution to fulfil it without reducing integrated luminosity it has been very recently devised [5].

In this paper we will not discuss the technical solutions for the upgrade that are described in other papers of this workshop and in more complete way in previous publications [6,7]. Rather, we will review the various upgrade and the installation plan and time, with an overview of the upgrade matrix of the various scenarios examined in this workshop: performance improving consolidation (PIC), upgrade scenario 1 (US1) and upgrade scenario 2 (US2). The cost breakdown for the main equipment will also be reported.

## GLOBAL VIEW OF FORESEEN UPGRADES

The total hardware renovation and upgrade of LHC are equivalent to manufacturing and installing about 1.2 km of a new accelerator, in various places of the LHC ring, as shown see Fig. 1 that gives the extend of the challenge. The LHC regions where important hardware upgrades will be carried out are evidenced: however the work will concern also surface buildings in P1 and P5 (for SC links and new powering) and along the full ring for an advanced magnet protection system. In term of timing the scheduled considered for the installation is the CERN official one at the time of the workshop (October 2013) that foresees a one year-long LS2 in 2018 and a two year-long LS3 in 2022-23. Comments on the feasibility from the point of view of the planning (both construction and installation) will be given in the section at the end of the paper.

## INSTALLATION DURING LS2

### *Cryoplant for superconducting RF in P4*

The cryogenic scheme and the main elements to be cooled are depicted in Fig. 2. In point 4 the refrigerator has to maintain cold the superconducting magnets of the arc and of the long straight section and on one side (right side of P4) also the inner triplet region at the left side of IP5. However in P4 the same cryo-plant is the refrigerator of the superconducting RF (SCRF) cavities, the accelerating system of the LHC. This has two inconveniences:

- The available power for the inner triplet and matching section magnets is less than in the other points.
- A magnet problem requiring the warm up of the magnetic system will affect the functionality of the SCRF system and vice-versa. The coupling may become a severe constraint when the machine will run at maximum energy and intensity, pushing all system at their limits.

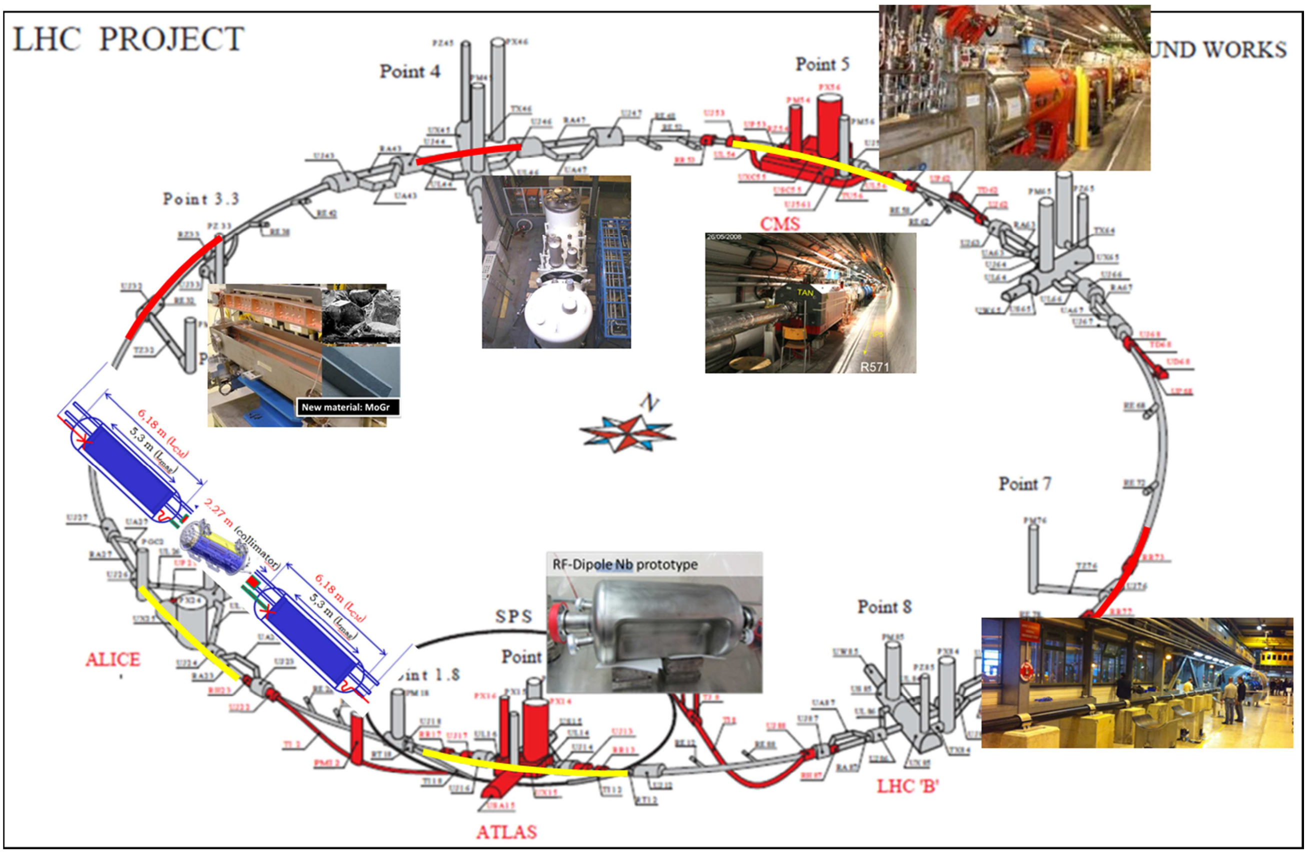


Figure 1: LHC ring areas where major works are required for the upgrade are marked with solid line. In yellow when works concern insertion regions (IRs) with experiments and in red when works concern IRs with only machine functions (length of solid lines not to scale).

The cure is to install a new cryo-plant in P4 for the SCRF system and fully decouple the magnet and the SCRF systems. The cryogenic power to be installed is in the range of 5 kW at 4.4K which is sufficient with considerable margin. However, since recently the idea of installing a second SCRF system (either 800 or 200 MHz [8] has been advanced, the power will be re-evaluated to cope with this possible additional system. Another system that may increase refrigeration needs in P4 is the superconducting solenoid of the electron lens (see dedicated paragraph later in the text). However its cryogenic power is so small to be in the shadow of the necessary margins.

### *Horizontal superconducting links in P7*

In Point 7 some electrical power converters (EPCs) feeding the superconducting magnets of long straight section are placed in alcoves called RR73 and RR77, near the betatron collimation system, intercepting a large fraction of the total beam losses in LHC, and therefore significantly increasing the probability of single event effects (SEE) occurence. A project, called radiation-to-electronics (R2E), is taking care of consolidating the EPC with new rad-hard systems [9]. However, a displacement of EPCs far from the accelerator is advantageous because:

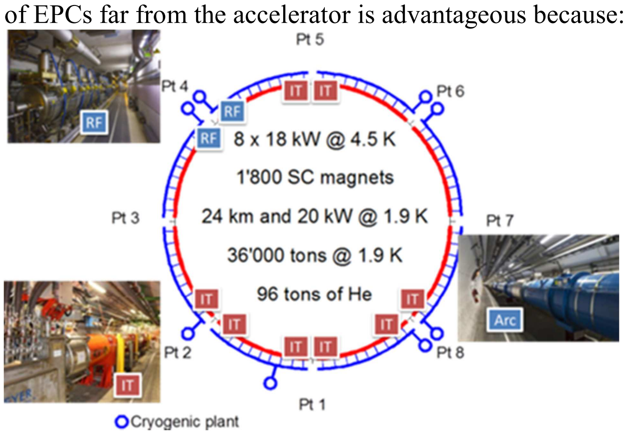


Figure 2: LHC cryogenics with indicated the main loads: Arc magnets (including MS), IT magnets and RF systems.

- Interventions on power converters are, and will remain, one of the main reasons of tunnel access. Removal of power converters from the tunnel will increase operational efficiency.
- In front of collimators the residual radioactivity will increase steadily up to high values. Safety principle ALARA calls for a radical action, if possible, to minimize radiation personnel exposure.
- The access to P7 requires special procedures for the ventilation of the tunnel, with even heavier consequences on operation time.

The solution that has been proposed is to place EPCs and relative distribution feed box (DFB), lodging the 300 K-4 K current leads, in a side tunnel, about 250 m far from main tunnel. In Fig.1 is shown this radial tunnel (TZ76) starting from P7 and reaching its access pit. This would require some twenty-four, 500 m long, cable pairs to connect the DFB to a service module in line with the beam pipe. To avoid a very high power dissipation and voltage drop, and also to remove the DFB from the tunnel as well, one has to use SC links [10]. To make use of the existing cryogenics, the system will rely on tapping supercritical helium at about 5 K from the LHC line C and using the enthalpy provided by an additional temperature rise, up to about 20-25 K. A flow of about 4-5 g/s is sufficient to provide a refrigeration power of 250 W for adsorbing the static and dynamic losses of the superconducting link and to provide the cooling the current leads. For the superconductor both $MgB_2$ and YBCO or Bi-2223 can be used. The cable is rated for 30 kA (in 600 A circuits). Test were done on a 2 m - 30 kA model and a 20 m - 25 kA prototype is ready for testing, see Fig. 3.

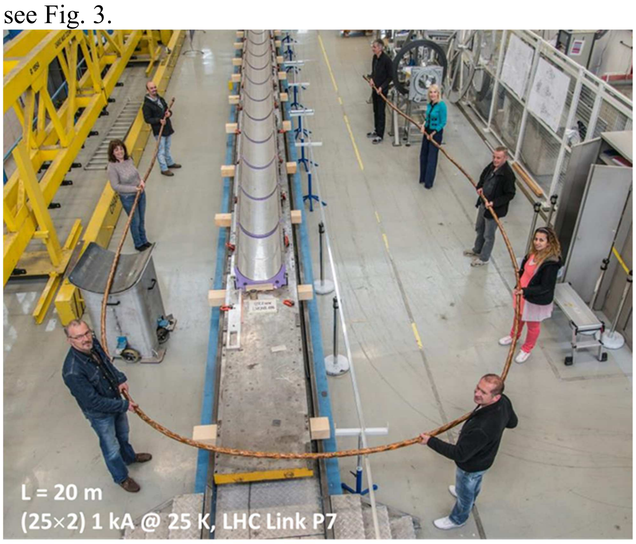


Figure 3: First 20 m long prototype of SC link (25 kA) for P7.

## *DS collimator for IP2 (ions) and P7 (protons)*

The issue of collimators in the LHC cold regions, namely in the Dispersion Suppressor (DS), has been raised at various occasions [11,12]. The particle losses in the DS regions are driven by three different mechanisms:

1. Protons losing energy due to diffractive scattering against the collimator jaws in both cleaning insertions of IR3 and IR7. This loss is not continuous since it is relevant only when a consistent part of the beam, is intercepted by collimators, i.e. during the short period when beam life-time is low. However their time scale ranges from a few ms to a several seconds: when a loss burst lasts fraction of seconds or longer, from a point of view of the energy depositions in the magnets, it should be regarded as a continuous loss.
2. Protons losing energy due to diffractive interaction at the collision point. This is a continuous process and it is important in P1 and P5, since it is proportional to luminosity.
3. Particles changing magnetic rigidities due to ultra-peripheral electromagnetic interactions of the counter-rotating ion beams at the collision point. This is a continuous mechanism, too, proportional to ion collision luminosity. It is relevant in P2 but also in P1 and P5, if the luminosity is as in P2.

These losses cannot be intercepted by the present momentum cleaning because diffractive losses are lost in the first dipoles of the DSs, acting as spectrometers, before reaching IR3. The only cure is to put collimators in the first high dispersion region, the DS zone where there are the first main dipoles of the arc. Since the filling factor in the arc is maximized for reaching the highest beam energy, the only viable solution is to create space by substituting a main dipole with an 11 T dipole. The 119 T·m (8.3T×14.3m) bending strength of an LHC dipole would be imparted to the beam by a 11T×10.85m new dipole, nicknamed 11 T dipole [13]. For convenience the 11T-11m dipole is split into 2×5.5 m long cold masses with the bypass/collimator unit in the middle, see Fig. 4, to minimize the orbit distorsion. The use of 11 T dipole,

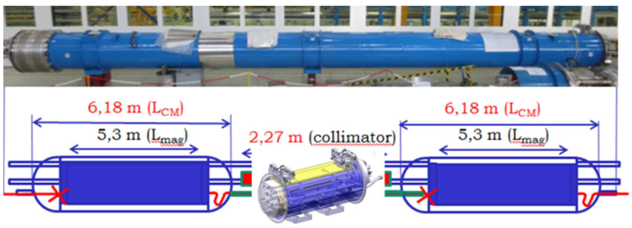


Figure 4: present LHC dipole (top) to be replaced by two $Nb_3Sn$ dipoles with by pass/collimator unit in the middle.

with the new challenging technology based in $Nb_3Sn$, would leave about 4 meters for two cold-warm transitions and a bypass cryostat lodging a 80 cm long collimator jaws, sufficient to reduce by factors 10 (IR7) to 50-100 (IR2 for ions) the radiation load compared to that on the present dipoles. The design of the collimator is complex but it not substantially different from the one of the main collimation system. The design of the by-pass poses serious technical and integration challenges, given the complexity of equipment and the very tight space left by the magnet. The design and construction of the 11 T is a new R&D, and the feasibility of this equipment has still to be demonstrated. In the frame of the CERN-Fermilab collaboration for the 11 T dipole, recently the second dipole short model build at Fermilab has reached and overcome the 11 T operational field [14]. However, instability issues call for a third model to give the final demonstration of the feasibility.

The 2013 review of the collimation system has established the following priority for 11T-DS collimators:

a. To install DS collimators in P2 during LS2, for intercepting the losses of the ions run and taking the maximum profit of the ALICE detector upgrade scheduled during LS2. Of course the same protection would be necessary in the DS regions around IP1 and IP5, since both ATLAS and CMS takes data during ions runs. However the decision is to give priority to ALICE, which has ions physics as main goals, and eventually limit the ion collision luminosity in P1-P5 just below quench limit.
b. To be ready to install collimators in the DS regions of P7 during LS2 for the proton beam losses. It seems that the need of DS collimation for the run after LS2 is marginal in P7, but it cannot be excluded. We plan to have the hardware ready (4 units) and then decide if installing it during LS2.
c. To be ready to install collimators in the DS regions around P1 and P5 for the proton continuous losses from the IPs during LS3. At present, the need of such collimation for HL-LHC parameters seems marginal, so experience in the next LHC run is necessary for a final assessment.
d. Eventually, to be ready to install DS collimation for P1 and P5 ions program, if ATLAS and CMS ions physics program and experience with P2 DS collimation call for it.

A problem is that while the system for P2, two 15 m long units, should be ready for installation at end of 2017, manufacturing the additional systems (four 15 m long units) needed for P7 requires one year more.

## *Low impedance collimators*

Low impedance collimators have been considered for a collimation upgrade since quite some times. Based on an extensive test campaign in HiRadMat facility on various materials[15], the most promising candidate for secondary collimator jaw is a molybdenum-graphite composite (MoGr) that, once coated with molybdenum is robust against impact of very high brightness beam and has a high surface electrical conductivity. In this way the impedance of collimators can be reduced by a factor ten, dramatically reducing the problem of beam instabilities driven by impedance.

The plan is to complete the design of such collimators and then install 2-4 of them during LS2 for testing and for getting experience, preparing for a massive campaign of substitution in 2022, during LS3 in view of the HL-LHC operation [16]. Note that the MoGr without coating might be used to increase the robustness of the present W tertiary collimators.

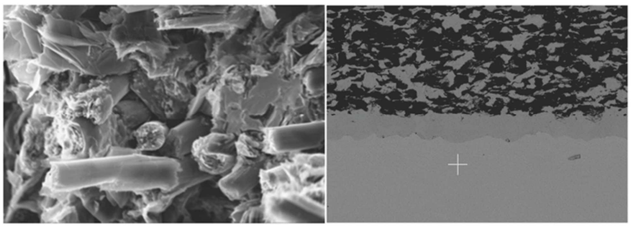

Figure 5: Molybdenum-Graphite (MoGR) composite reinforced with Carbon Fibers (left) and MoGR coated with Mo (right), with an intermediate Carbide layer (darker gray layer).

Somehow the plan can be accelerated or slowed down according to actual needs (to be verified during next run) and to available resources. Indeed, since collimators are in room temperature regions, access is much easier (with respect to the DS region, which is in the continuous cryostat). Also note that empty slots for new secondary collimators are already available for a quick installation (one of this slots will be used for prototyping at the LHC). Would an additional extended technical winter stop be present, as envisaged at the workshop, probably the installation of a prototype could be anticipated during such stop. Then, if the experience is positive, a massive campaign of substitution of secondary collimators may be carried out already in LS2, with the scope of reducing the impedance of the total collimation system by more than a factor two.

This upgrade is to be considered also a renovation of the collimation that can cure the long term wear of the system and, as such, it is also an unavoidable consolidation plan.

# INSTALLATION DURING LS3

## *Interaction Region (Q1-Q3, D1)*

The change of the inner triplet (IT) quadrupoles with new magnets of larger aperture is the backbone of the upgrade. These magnets will reach the threshold of radiation damage (typical mechanical weakening and loss of dielectric strength in the insulators), estimated to be about 20-30 MGy [17] at around 300-400 $fb^{-1}$ of accumulated luminosity. The triplet is a typical example of PIC: we profit of the necessary replacement of the IT quadrupoles to install new quadrupoles with larger aperture, in order to increase the luminosity reach. Recently their coil aperture has been fixed to 150 mm [18] to maximize the upgrade performance, with an operational gradient of 140 T/m. These parameters imply a peak field of more than 12 T on the coils, requiring the use of $Nb_3Sn$ technology which has been principally developed in the USA via the DOE Conductor Development Program and LARP [19], and more recently at CERN [13]. The more than doubling of the quadrupole aperture entails a new larger TAS (the first absorber between detector and machine) and an a larger aperture of all magnetic elements of the interaction regions, where the two beams are circulating in the same beam pipe: separation dipole D1 and corrector magnets of various types, with a new beam screen supporting a thick W-shield (up to 16 mm) to reduce radiation on the superconducting magnets. The system has been described in various papers [13,20,21,22], so here we limit our discussion to installation time.

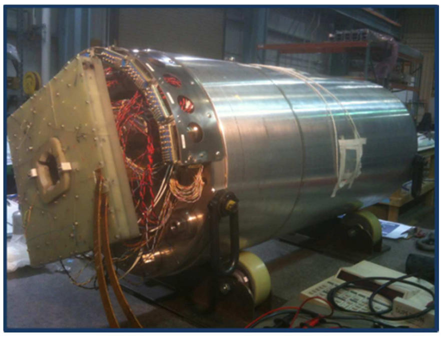

Figure 6: The cold mass of the HQ02 120 mm aperture quadrupole, designed and built by USA-LARP. This magnet, near to the final design of HL-LHC IT quadrupoles, routinely passed 12 T of peak field during power test at Fermilab. Picture taken at LBNL after structure assembly.

The plan is to carefully prepare installation by carrying out a full test in operational conditions of a complete "string": Q1-Q2a-Q2b-Q3-Corrector Package-D1, to be done at least one year prior installation, to check all integration problems. Having the triplet ready for installation in 2022-23 is feasible, although with reduced margin: the plan is today to have Q1-Q3 delivered as in-kind contribution by USA and D1 by KEK.

A critical point is the de-installation of the present triplet, which will be highly radioactive. A prudent plan would require about four months for radiation "cooling", six months for de-installation and one year for installation and commissioning of the new equipment. This leaves just two months of margin over the two year shutdown duration. The main concern is not the time duration, which looks sufficient, but the availability of personnel and CERN services to carry out parallel installation in the various IRs.

Before concluding this part one has to take not of the good suggestion, made at the workshop by the CMS coordination, of studying an anticipated removal of the TAS already in LS2, to reduce dose to personnel (the TAS is the most radioactive equipment of LHC). In such a case a special removable insert should reduce the aperture form the 60 mm of the new TAS to 35 mm, the present baseline. In such a way, during LS3 only the job of taking away the removable TAS insert will be left, making the inner diameter 60 mm wide, the aperture needed for the 10-15 cm $\beta^*$ target.

## *Matching section magnets*

Increasing the aperture of more than a factor two in the IT, and consequently decreasing $\beta^*$ by a factor almost four, strongly affects the aperture of the matching section (MS) optics elements, especially D2, Q4 and Q5 with their corrector magnets and the neutral absorber, called TAN. In addition the situation is complicated by the fact that the crab cavities will be installed between Q4 and D2.

Here we summarize the baseline plan for the matching sections:

1. The present TAN needs to be replaced with a new one with larger aperture and possibly with different geometry. Optimization of the TAN geometry (Which has to protect also the CC, is under investigation). It is just worth remembering that the present TAN hosts some physics detectors, too.
2. The new D2 recombination dipole will feature an aperture of 105 mm (vs. a present of 90 mm) and higher bending strength than today, which will require increasing peak field (not an easy goal, because of excessive flux in the yoke, due to the same field direction along the two apertures) or its magnetic length.
3. The aperture of Q4, which is the first two-in-one quadrupole moving from IP, will increase from 70 to 90 mm, and will be longer than the present magnet.
4. The Q5 also will be increased in aperture (at least 70 mm from the present standard 56 mm) and length. A first possibility is re-using the present Q4, but one would need to increase its gradient or its length. The first case is maybe possible because one can gain available peak field by passing from 4.4 K (present operating temperature) to 1.9 K as foreseen in HL-LHC configuration. The issue is under study.
5. As above mentioned, the operating temperature of the matching section will pass from 4.4 K, as it is at present for all stand-alone magnets, to 1.9 K by means of pressurized superfluid helium as for the LHC arc and inner triplet.
6. A change is required in the optics of the MS of IR6, as required by the new optics scheme called ATS [23]. This will require the installation of two additional Q5 (MQY) quadrupoles to increase the integrated strength
7. At least four chromaticity sextupoles will have to be added at Q10 position close to the interaction points for third order resonance compensation in with the ATS optics.

The change of current and of refrigeration scheme of the MS magnets gives the opportunity to radically re-designing the cold powering of these magnets, as discussed in the next section.

The deep modification of the MS [24] requires a lot of design work because there are many superconducting magnets. Even though of standard Nb-Ti technology, integration is tighter than in the present LHC and de-installation will have certainly to respect ALARA procedures. A first evaluation based on LHC installation experience indicates that all hardware can be tested and made ready for installation by 2022. The two year duration of LS3 seems adequate for the installation of the new MS, provided that sufficient resources are available.

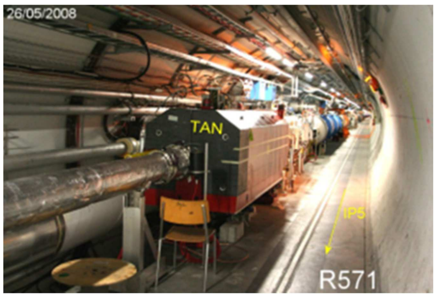


Figure 7: The TAN and MS magnets region in IR5(right)

## *Crab cavities*

The LHC beams collide with an angle to avoid multiple collisions in the detectors and parasitic collisions outside. The collision angle must also guarantee a beam separation as large as 12 σ (for the intense HL-LHC beam) to reduce long range beam-beam interactions to a level to be negligible. Because of the very small β* the separation angle become large, 590 μrad, while in the nominal LHC is 290 μrad (separation is 9.5 σ and β* is 55 cm), with an important reduction of the luminosity due to worsening of the geometric factor (length of the bunch overlapping region normalized to the bunch length), as shown in Fig. 8.

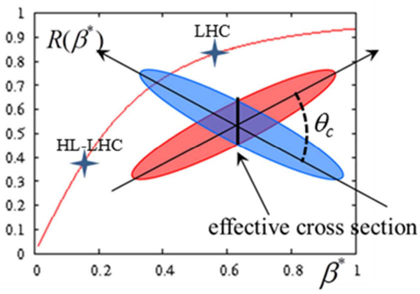


Figure 8: Luminosity reduction effect of the a crossing angle $\theta_c$ between colliding bunches vs. β*.

The crab cavities (CC) can provide a rotation to the bunch, seen as rigid body, to recover the geometric factor and restoring the full luminosity gain given by the reduction of β*. Of course an identical counter rotation must be given to each bunch at the opposite side of the IP, to close the bump.

In addition to this function, CC have been recently proposed for controlling the pile up density [5] a concept that is becoming more and more important for the experiments at very high luminosity. Here we will not discuss the crab cavity physics and technology that can be found in other papers [25, 26]: we will mainly discuss integration issues and plan.

To be most effective, i.e. to give the maximum rotation at IP per unit of transverse voltage kick, the CC have to be placed where the β-function is the largest and the counter-rotating beams are still parallel and at normal separation of 194 mm in separate vacuum chamber (before D2 start to recombine the two beams). So a space must be found by enlarging the distance between Q4 and D2, to lodge the CC unit. This poses some challenges for integration of the 10 m long CC cryostat and the place for the RF infrastructure (Klystron, modulator, controls, etc.) in an area far from the interaction point gallery.

As far as feasibility and operation issue of CC one has to underline that this is an absolute *prima* in two respects: use of CC on hadrons and use of compact CC. So far, we have the very encouraging results of 2013 on the first three types of single CC, tested in vertical and all reaching or passing the target voltage of 3.4 MV, see Fig. 9. Second generation cavity prototypes are under construction, to be eventually assembled in cryo-modules. A proof-of-principle test has been proposed and approved in the SPS, for all cryo-modules that will be manufactured for this second generation. The SPS test is critical to assess the ability of controlling unwanted beam effects.

The CC project heavily relies, like the IT quadrupoles, on the effort the US-LARP program. The plan and the issues can be summarized as followed:

1. The CC cryo-module will be placed between Q4 and D2, as near as possible to D2.
2. To allow both correction of geometrid factor and control of the pile up density, four cavities per beam on each IP side are necessary.
3. Each of the eight CC units will be housed in one 2 K saturated He II cryo-module, interleaving the cavities of the two beams (see Fig. 10).
4. CC second generation must be ready by 2015, tested and then assembled in cryo-modules for testing in SPS that must start in 2017 at latest. SPS test results must be conclusive well before the stop for LS2.
5. Construction of CC can start only in 2018 (although prototyping of a possible generation 2.1 or 3.0 and procurement of main tools and material will continue all along 2016-17.

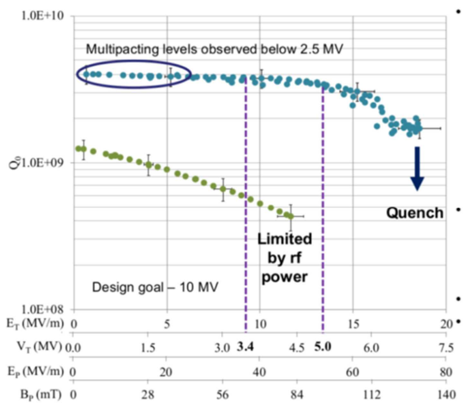


Figure 9: Results of the test of the RF dipole CC (courtesy of J. Delayen, ODU university and J-lab)

Clearly the time for manufacturing and testing the four complete cryo-modules, plus two spares, of CC by beginning of 2022 is tight, although possible.

In addition one should take a decision on the space needed for the RF infrastructure and on location. Today the excavation of a lateral hall seems necessary because the space in the RR alcove it is too small and RR itself is too far from the cavity (problem of phase control). This hall will be expensive, and even more expensive would be a dedicated new access pit that appears mandatory. However, from the point of view of the logistic this can satisfy also other equipment request and the civil engineering works can take place during LS2, without interfering with LHC works.

In conclusion the CC project can fit inside the LHC schedule as for October 2013, but clearly a longer LS2, to allow early excavation of the new lateral halls, and a shift of LS3 by one year will be both welcome.

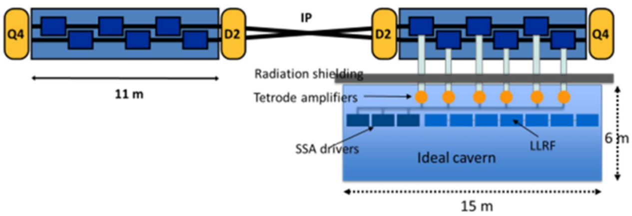


Figure 10: schematic of the crab cavity concept around IP and room required for lateral hall.

## *Availability: cold powering and QPS*

The reason for displacing the power converters and the feed-boxes outside the LHC tunnel, when they are in the most highly radio-activated zones, has been already presented in a previous section *Horizontal superconducting links in P7.* Since all IR optics elements will be replaced by new ones with different characteristics (all requiring larger operating current than the present ones), it is also a chance to rationalize the cold powering according to modern criteria.

Considering the lack of space for proper integration of the new equipment infrastructure in the IR1 and IR5 and the dose of radiation that will inevitably affect the zone when producing 250 $fb^{-1}$/year, all new power converters and distribution feed-boxes (both the one for the triplet and the one for the matching section magnets) will be removed on surface by means of powerful (150 kA) superconducting links that will bring the current at cold with the minimal power loss, like depicted in Fig. 11. This will solve the problem of SEE and will considerably increase the availability of the LHC, with benefit for the integrated luminosity.

Last but not least, the removal of EPCs and especially of the DFBs, will dramatically decrease the radiation dose to personnel in charge of intervention and maintenance of such equipment, beside easing the maintenance itself from a technical point of view. This ALARA argument is very important and it is high in the priority list of the HL-LHC project.

Detailing the plan for cold powering of all magnetic elements would requires a too long and tedious list. Here it suffice to mention that we will need eight SC cables, about 300 m long, rated between 150 and 200 kA, with 5 kV voltage (in terms of power capacity this mean about 1 GW per cable!). The amperage is composed of different circuits, of which some, the quadrupole triplet, rated at 20 kA). Despite the big technical challenge represented by these superconducting lines, the project can fit into the given schedule, provided that the needed civil engineering on surface and the small pit for the cable passage surface to underground is done in LS2, which should not pose a problem.

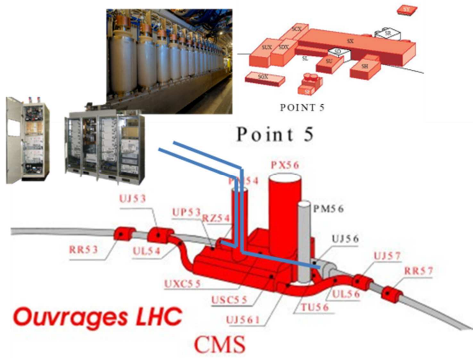


Figure 11: removal of power converter and DFBs on surface at P5 by means of SC link (blue lines)

Important challenges for the system, beside the superconducting cables, are given by the need of assuring the proper support in the vertical pit and by the full powering system, including connection and distribution boxes , given the huge amperage and the many circuits to connect.

The 20 kA HTS current leads will be based on an extrapolation of the present LHC 13 kA design. The IR1 and IR5 SC links and new DFBs will be cooled by means of new dedicated IT cryo-plants (see next subsection)

The quench protection system (QPS) is one of the critical systems of LHC requiring more intervention, and indeed is among the systems more contributing g to the machine down.-time. Already in LS1 important improvements will be carried out. However, also profiting of necessary revamping of electronics, dated of year 2000s and that will be obsolete in the 2020s, we envisage for HL-LHC a radical solution: to displace on surface as much as possible of the electronics boxes that today are underneath of the dipole magnets, with clear benefit for availability, ease of maintenance and, again last but not least, the dose to personnel.

Germinal ideas have been discussed, the next step, after LS1 completion, is to study a solid technical solution and to make a realistic plan.

## *New IT cryoplants*

Much higher radiation is expected escaping from IP1 and IP5 debris because of the increased luminosity in HL-LHC [27]. A large fraction of the power will be intercept at 4-10 K, by the tungsten shield, thermally connected to the beam screen. In total about 600 W will be intercepted in the IT-D1 beam screen and about the same will be absorbed by the coil and cold mass at 1.9 K. An extra cryogenic load will be given also by the much larger amperages of the IT quads and by the change of D1 from normal conducting to superconducting type. In Fig. 12 the needs of cryogenic power are represented in the various scenarii in terms of available power for e-cloud after all known losses have been subtracted from the refrigeration capability.

Refrigeration needs will considerably increase also in the MS because of increased amperage of the magnets and their cooling at 1.9 K, and because of the presence of CC cryo-module, as well as of the SC links. Indeed, if no additional cooling power is added, the helium circuit in the MS may increase the temperature of 0.1-0.15 K according to the various scenario, dangerously reducing the margin for the stand-alone quadrupoles.

The baseline is to cope with the increased need of refrigeration by installing two new cryo-plants, each one capable of at least 12 kW power at 4.2 K. The cryogenic infrastructure will be modified to separate the QRL of LSS, serving the MSs, the CC and the IT, from the arc QRL serving the continuous cryostat of the arc (regular lattice and DS). By virtue of this new sectorization, a stop of refrigeration of the LSS will not cause a warm up of the arc and vice versa, greatly increasing the availability and the flexibility. Sectorization can be engineered in such a way that each IT new cryo-plant could serve as redundancy for the adjacent arc cryo-plant, of course with degraded operation mode. To make this redundancy most effective, installation of 18 kW plants will also be considered. Another advantage is to modify the cooling circuit in the IP1-5 such that the new cryo-plants could also serve as redundancy for the experimental magnet cryo-plants, and vice versa, again maximizing the flexibility in order to increase availability. The study of the new cryo-plants for IP1 and IP5 will be launched after LS1, since they are not on the critical path for LS3. However installing two new large cryo-plants necessitates an increase of space, service and infrastructure therefore integration study will be advanced in 2014.

The possibility to inject and accelerate beams with the HL-LHC characteristics relies on the effectiveness of the scrubbing in reducing the SEY in the dipoles down to 1.4 or lower to avoid multipacting. The new HL-LHC triplets and the D1 separation dipoles in the Interaction Regions (IR) 1 and 5 will have beam screens coated with low SEY materials and, if necessary, they will be equipped with clearing electrodes to suppress multipacting. Similar countermeasures might have to be applied for the triplets and D1 in IR 2 and 8.

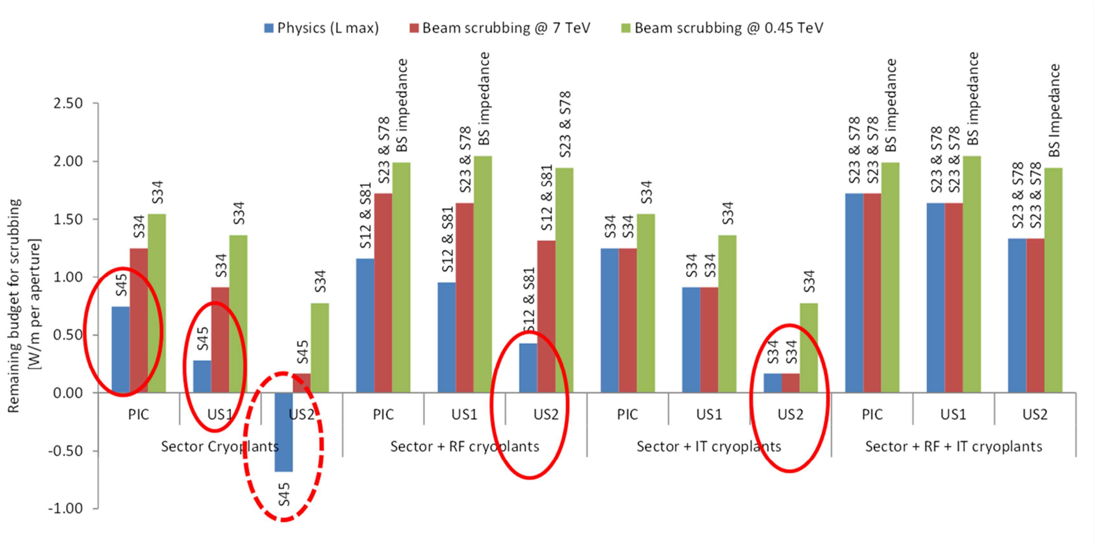


Figure 12: Power available in the arc once all known consumption are deduced, in the various scenarios (PIC, US1 and US2) with various configuration of LHC cryo-plants (RF means new cryo-plant in P4, IT means new cryo-plant in P1 and P5). In red are circled the case of impossible or very dangerous operation. A good margin is 1W/m and is assured only by installing all three new plants

## *Long range beam-beam compensating wires*

Use of electric wires parallel to the beam to compensate the long-range effect of the inter-beam interaction has been proposed for LHC long time ago [28], see Fig. 13. However for various reasons practical work to design a prototype for the LHC has started only recently. This equipment may allow reducing the crossing angle, reducing the demands on crab cavity or even constituting, in the case of flat beams, a possible mitigation plan in the unfortunate case that CC would not be viable. The plan calls for a test of preliminary prototype, built using the present collimator technology [29], in LHC by 2015-2016 and then the construction of a final prototype with specific technology (although the vicinity to the beam will always require collimator-like design), to be installed during LS2 for having it tested in best configuration on LHC beam during RunIII. This should allow building the final systems, with eventual corrective actions, in time for LS3.

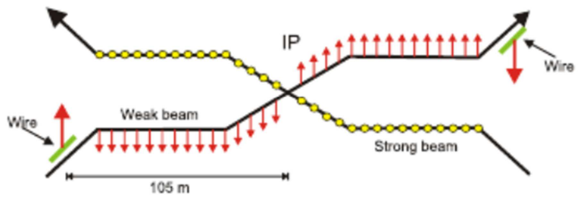

Figure 13: Effect of wires, compensating the effect of the long range beam.-beam interaction (here schematized in the strong-weak representation)

## *New collimation and halo control: electron-lens and crystals*

There are two main functions of the collimation system in the high-luminosity IRs:

1. halo cleaning and protection of the triplet magnets;
2. cleaning of physics debris products.

The collimators on the incoming beam side that provide the first functionalities might also be used for background optimization. For the present LHC, the IR aperture limitation with small β* is found at the triplet magnets and one single pair of horizontal and vertical tertiary collimators (TCTs) is sufficient for the first function. This situation will change for the HL-LHC optics baseline, potentially requiring additional TCT-like collimators further upstream in the MS, at appropriate phase advances to shield the Q4 and Q5 magnets. Details on the numbers and locations of required TCTs are being studied.

For the physics debris, in addition to the DS collimation concept previously discussed, the MS layout changes for HL-LHC will impose obvious updates of the TCL collimators that are used to catch physics debris products (they have to follow the new magnet positions). The TCL layout is being upgraded in LS1 to have 3 collimators in cells 4, 5 and 6 at each IP side. This baseline is being studied also for the HL-LHC and it seems promising, but simulations are to be performed for the final layout. Other issues, like collimator needs for CC protection and effect of CC field on far debris losses, are being addressed.

Since a few years, following the promising results achieved at the Tevatron and under the umbrella of LARP collaboration with the collimation team, CERN is considering the possibility of controlling the beam halo through a slow diffusion of the particle by means of hollow electron beams which overlapping for a few meters with the proton beams (one device per beam). Investigation is going on [30] and the plan today is to study its application directly in the LHC without passing through a test in the SPS, since the functionality of the hardware has been already positively assessed in the Tevatron beam, see Fig. 14. The decision if this system would be necessary for LHC and HL-LHC will be taken after enough operational experience is accumulated after 2015: the RunII will give important information on the halo population and loss/repopulation mechanism and after that other possible alternative halo control system (tune modulation, feedback system and suitable use of LR b-b interaction) will be also studied in detail. A revised estimate of quench limits and beam lifetime will be needed. Effort has started at CERN with the ambitious goal to achieve a design report of such system, based on a conceptual design report provided by the Fermilab team, in order to be ready for possible implementation during LS2, which is a very challenging goal.

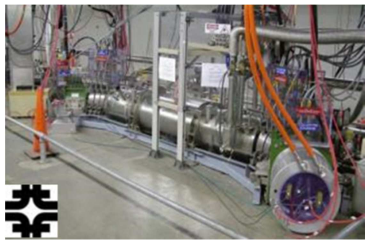
Figure 14: the Tevatron e-lens (e-gun not shown)

Crystal collimators have shown their interest with the success of the UA9 experiment in the SPS [31]. Here it is more difficult to make a plan since the suitability for LHC and the eventual R&D needed will be clarified after the first test in 2015 on LHC beam. Potentially, the crystal collimation is a change of paradigm, virtually all the beam halo is extracted onto, and absorbed by one single collimator, see Fig. 15. Crystal collimation is expected to provide a cleaning improvement due to reduced dispersive losses in the DS and reduced impedance. This scheme could be particularly interesting for the ion collimation in IR7. The time scale is not yet clear, however since the hardware is not bulky, once proved to be viable, a few years might be sufficient to design, manufacture and install this equipment. The integration into a safe LHC operation and the absorption of high-power channelled beams will have to be demonstrated.

It is important to note that the two advanced techniques discussed above are only helping betatron collimation and cannot improve losses in the interaction regions from physics debris. Hence, it is important to continue R&D on the 11 T dipole solution coupled with "standard" LHC collimators.

Both e-lens and crystal are not on the critical path for HL-LHC provided that a decision is taken before LS2. The e-lens has also to be scrutinized for integration issues, since the only region where they can be installed is in IR4 where the special dog-leg enlarges the inter-beam distance from 194 to 420 mm.

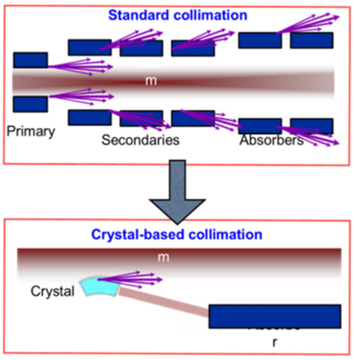

Figure 15: principle of crystal collimation

### *RF harmonic system*

The advantage of a harmonic system of the 400 MHz LHC main RF cavities to increase the luminosity has been put through very early in the LHC upgrade studies, envisaging either an 800 or a 1200 MHz SCRF system [32]. A study of the possible benefit, and issues to overcome, of a 800 MHz have already started, also because of the synergy with the energy recirculating linac envisaged for LHeC. In the frame of the collaboration with the university of Stuttgard (Germany) two 800 MHz SCRF cavities are under construction and could be used as prototype for HL-LHC.

Very recently in the frame of the preparation for this workshop the possibility of using 200 MHz cavities has been put through and compared with the use of the 800 MHz system [8]. The idea is to use the 200 MHz as main accelerating system and the present 400 MHz would become the harmonic system, at least in certain phase of the operation cycle. The proposal is too recent to be examined in terms of integration. However is clear that a 200 MHz system may be too large for the tight space of LHC, even in the dog-leg of IR4, if built in elliptical shape: the proposal is indeed to use Quarter-wave type cavity, which would pose less problem of space. In any case careful integration studies should be carried out before validating this idea.

## IMPLEMENTATION MATRIX AND COST

For the operation-shutdown schedule, we refers to the official CERN plan of October 2013, see Fig. 15.

The main difficulty for the implementation works foreseen for LS2 concerns the 11 T dipole – DS collimation. Indeed, six months of delay have been accumulated, virtually reducing to zero all previous margins. Further, the larger than planned engagement of the CERN teams for the LS1, which is of course the priority of all equipment groups, has adverse consequence on the personnel availability. One year of shift in the end of LS2 is certainly welcome for this project.

A short shutdown, called extend year end technical stop (see slim red box in the schedule of Fig. 15) would be extremely useful to install low-impedance collimators prototype and to advancing infrastructure works for the P7 SC link as well as for the new cryo-plant in P4. This also help to fit theLS2 works in the one year schedule. The extension of LS2 to 18 months is beneficial, especially for the 11 T project.

The extended stop, in conjunction with the shift of at least six months of the LS2 start, is also necessary to install the CC in the SPS and to properly carry out beam tests in 2017-18.

The shift of LS3 by one year, widely discussed att eh workshop is probably necessary for the CC project and it is a welcome (but not mandatory) for the inner triplet and the other equipment. The shift of LS3 is not mandatory because we can always devise a plan where the inner triplet and MS magnets, with cryogenics and cold powering, are installed in the LS3 and the CC are installed in the subsequent long shutdown. The HL-LHC project needs two years for installing and commissioning all the hardware. An extension by six months is certainly useful, however an even longer shutdown, especially if coupled with a further shift, may suggest a new scenario (for example a merging of LS2 and LS3). Indeed to increase the integrated luminosity we should not delay too much the installation of the new triplet that has very good chance to be ready by 2022, also thanks to the USA and Japan contribution.

In Fig. 16 is reported the implementation matrix, according to the scheme reported in the document for the workshop preparation (https://espace.cern.ch/ReviewWorkshop/Timetable/RLIUP%20workshop%20Full%20View%20timetable.pdf). Here we remind that PIC (performance Improving consolidation) has the goal of reaching 1000 $fb^{-1}$ limiting the upgrade to those equipment that needs to be replace for wear and damage, like the inner triplet; US1 (upgrade scenario 1) has the goal of reaching 2000 $fb^{-1}$; US2 has the goal of reaching the full goal of the upgrade, 3000 $fb^{-1}$.

The Fig. 16 contains also a budgetary evolution of the material cost, done in the CERN accounting system. A rigorous bottom-up with management validation budget will be carried out in 2014.

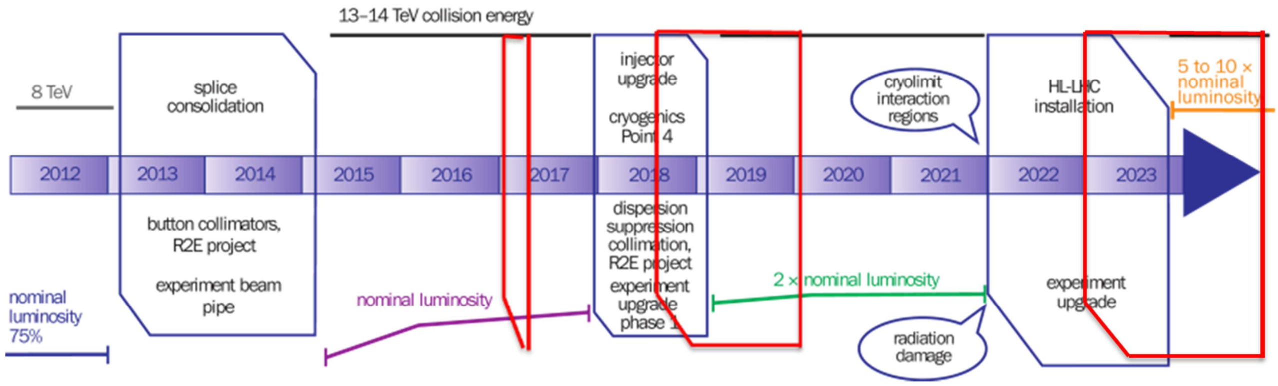


Figure 15: CERN ten year plan at the time of the RLIUP workhop. The blue boxes indicate the major shutdowns (winter stops not indicated). The red boxes indicating possible, or desired, modification to shutdown schedule.

The budget figures are substantially the ones of end 2011, at the beginning of the FP7 HiLumi design Study, and do not contain:

- The cost of possible lateral galleries, nor their access pits, for CC infrastructure.
- The cost of the SCRF $2^{nd}$ harmonic system and its infrastructure.
- The cost of the e-lens, crystal collimators and high band feedback system.

The cost of the LRBB wire is very approximate since the hardware development has just started. Both this equipment and the SCRF harmonic system are not in the official baseline. However they are considered important and even essential (LRBB wire) for reaching the HL-LHC targets.

In the same table of Fig. 16, it is indicated the possible in-kind contributions from non-member States. The in-kind contributions will reduce the CERN cost, of course; however, given the different accounting system, the value of the contributions may not decrease the CERN cost of the same amount. In this respect the figures shown in the table are to be considered as “CORE cost”, very much like in the LHC experiments. The figures do include all cost of technical infrastructure related to the equipment of the upgrade, but not the cost of the consolidation needed to maintain operational the various services and infrastructure for the LHC machine.

## CONCLUSIONS

The HL-LHC is a very challenging project, aiming at improving a machine already very optimized. It requires a very high quality performance form the LHC Injector complex and a global revision of the machine parameters.

New concepts are applied to reach the upgrade goals, like the luminosity levelling, the ATS optics, the crab kissing scheme and the bunch rotation by means of CC. Novel advanced components will be used to dramatically improve the main performance of the two main accelerator technology: magnets and RF cavities. Superconducting magnets capable of up 12 T in very large bore (the IT quadrupoles) and very compact superconducting cavities capable to manipulate the proton bunch in the transverse space.

We have a solid plan to successfully finish the R&D for all various equipment and, thanks also to the new CERN schedule discussed during this workshop, we are optimist to be able to satisfy the installation schedule. The main uncertainty is at present, and probably will remain, the availability of adequate resources of personnel, in CERN and in all collaborating Institutes.

## ACKNOLEDGEMENTS

We warmly thank all people that are involved in the HL-LHC and that have provided useful information and material for this paper.

| LS2 - 1 y (14 months access) | | LS3 - 2 y (26 months access) | | | | | |
|---|---|---|---|---|---|---|---|
| | PIC | | US1 | US2 | Cost (MCHF) | | In kind |
| | *LS2* | *LS3* | *LS3* | *LS3* | | | in part |
| P4 new cryoplant | Y | | | | 15 | | |
| H SC link P7 | Y | | | | 5 | | |
| IR (IT,D1, TAS) | % | Y | | | 210 | | YES |
| P1-P5 cryoplant | % | Y | | | 75 | | |
| SC link (EPC&DFBX on surface) | % | Y | | | 40 | | |
| Collimators IR | | Y | | | 10 | | |
| Collimators MoGr | % | Y | | | 15 | | |
| Collimators for INJ &TCLA Q4/Q5) | | Y | | | 5 | | |
| DS cryocoll.(11T) P2 | Y | | | | 20 | 395 | |
| LRBB comp.wires | | | Y | | 10 | | |
| DS cryocoll.(11T) P7 | | | Y | | 25 | | |
| DS cryocoll (11 T) P1-P5 | | | Y | | 40 | | |
| SC link (EPC&DFB on surface) for MS | | | Y | | 20 | 95 | |
| MS new layout (P1-P5) and Q5 in P6 | | | | Y | 30 | | YES |
| Machine & Magnet QPS (Availability) | | | | Y | 25 | | |
| CC cavity P1-P5 | | | | Y | 95 | | YES |
| SCRF 2nd Harmonic | | | | Y | | | |
| Crystal Coll | | | | Y ? | | | YES ? |
| Halo control (e-lens) | | | | Y ? | | | YES |
| High Band Feedback System | | | | Y ? | | 150 | |
| Studies | | | | | 10 | | |
| Other systems (Studies, Vacuum, Diagnostics, Remote handling | | | | | 30 | | |
| Infrastructure, Logistics, Integration,Installation HWC | | | | | 130 | 170 | |
| **Total** | | | | | **810** | **810** | |

Figures 16: Implementation matrix and material cost, in CERN accounting system, of the HL-LHC project. See text for explanation. The symbol "Y" means Yes (full implementation) and "%" means partial implementation. The "?" is used to tag equipment that today are not in baseline.

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