# High Luminosity Large Hadron Collider A description for the European Strategy Preparatory Group



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# Abstract

The Large Hadron Collider (LHC) is the largest scientific instrument ever built. It has been exploring the new energy frontier since 2009, gathering a global user community of 7,000 scientists. It will remain the most powerful accelerator in the world for at least two decades, and its full exploitation is the highest priority in the European Strategy for Particle Physics, adopted by the CERN Council and integrated into the ESFRI Roadmap. To extend its discovery potential, the LHC will need a major upgrade around 2020 to increase its luminosity (rate of collisions) by a factor of 10 beyond its design value. As 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), will rely on a number of key innovative technologies, representing exceptional technological challenges, such as cutting-edge 13 tesla superconducting magnets, very compact and ultra-precise superconducting cavities for beam rotation, new technology for beam collimation and 300-metre-long high-power superconducting links with zero energy dissipation.

HL-LHC federates efforts and R&D of a large community towards the ambitious HL-LHC objectives and contributes establishing the European Research Area (ERA) as a focal point of global research cooperation and a leader in frontier knowledge and technologies. However, it relies on a strong participation from outside the (ERA), in particular leading US and Japanese laboratories, which will facilitate the implementation of the construction phase as a global project. The proposed governance model is tailored accordingly and may pave the way for the organization of other global research infrastructures.

# 1. Concept and objectives

# 1.1. Context

The Large Hadron Collider (LHC), run by CERN at the Franco-Swiss border near Geneva, is the largest instrument ever designed and built for scientific research. Successfully commissioned in March 2010 for proton-proton collisions with a 7 TeV centre-of-mass energy, is delivering 8 TeV centre-of-mass proton collisions since April 2012. The LHC is pushing the limits of human knowledge, enabling physicists to go beyond the Standard Model: the enigmatic Higgs boson, mysterious dark matter and the world of supersymmetry are just three of the long-awaited mysteries that the LHC will unveil. **The announcement given by CERN on 4 July 2012 about the discovery of new boson at 125-126 GeV, almost certainly the long awaited Higgs particle,** is the first fundamental discovery, hopefully the first of a series, that LHC can deliver. Thanks to the LHC, Europe has decisively regained world leadership in High Energy Physics, a key sector of knowledge and technology. The LHC can act as catalyst for a global effort unrivalled by other branches of science: out of the 10,000 CERN users, more than 7,000 are scientists and engineers using the LHC, half of which are from countries outside the EU.

The LHC baseline programme has the goal of producing first results in the 2010-12 run aimed at an integrated luminosity<sup>1</sup> of more than 20 fb<sup>-1</sup> by the end of 2012. Today progress towards this goal is advancing well, meeting or even exceeding all intermediate milestones. After attaining the **maximum energy of 14 TeV centre-of-mass energy** at the end of 2014, it is expected that the LHC's will reach the **design luminosity<sup>2</sup> of 10<sup>34</sup> cm<sup>-2</sup> s<sup>-1</sup>** in 2015. This peak value should give a total integrated luminosity over a one year of about 40 fb<sup>-1</sup>. Then in the period 2015-2020 LHC will hopefully increase the peak luminosity: indeed margin have been taken in the design to allow, in principle, to reach about 2 times the nominal design performance. The baseline programme for the next ten years is depicted in Fig.1, while in Fig. 2 are the graphs of the possible evolution of peak and integrated luminosity.



Figure 1: LHC baseline plan for the next ten years. In terms of energy of the collisions (upper line) and of luminosity (lower lines). The first long shutdown 2013-14 is to allow design parameters of beam energy and luminosity. The second one, 2018, is for secure luminosity and reliability as well as to upgrade the LHC Injectors.

After 2020 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 half the statistical error in the measurements will be more than ten

<sup>&</sup>lt;sup>1</sup> **Integrated luminosity** is a quantity proportional to the number of recorded collisions, measured in inverse femtobarns, fb<sup>-1</sup>

<sup>&</sup>lt;sup>2</sup> Luminosity is the number of collision per square centimetre and per second,  $cm^{-2} s^{-1}$ 

years at the end of 2020, assuming to reach effectively twice the nominal peak performance, see Fig. 2 right. Therefore to maintain scientific progress and to explore its full capacity, the LHC will need to have a decisive increase of its luminosity. That is why, when the CERN Council adopted the European Strategy for Particle Physics<sup>1</sup> in 2006, its first priority was agreed to be "to fully exploit the physics potential of the LHC. A subsequent major luminosity upgrade, motivated by physics results and operation experience, will be enabled by focused R&D". The European Strategy for Particle Physics has been integrated into the ESFRI<sup>2</sup> Roadmap of 2006 and its update of 2008, and the priority to fully exploit the potential of the LHC has been reaffirmed by CERN Council in various sessions.

This new phase of the LHC life, named as High Luminosity LHC (HL-LHC) has the scope of enabling to attain the astonishing threshold of 3000 fb<sup>-1</sup> in 10-12 years.

All the hadron colliders in the world have so far produced a total integrated luminosity of about 10 fb<sup>-1</sup>, and the LHC will deliver about 20 fb<sup>-1</sup> at the end of 2012 and about 300 fb<sup>-1</sup> in its first 10 years of life. The High Luminosity LHC is a major, extremely challenging upgrade. For its successful realization a number of **key novel technologies** have to be developed, validated and integrated. The work is initiated with the FP7 Design Study **HiLumi LHC** which, approved by EC in 2011 with the highest mark is instrumental in initiating a new global collaboration for the LHC that matches the spirit of the worldwide user community of the LHC experiments.



Figure 2. Left: possible peak luminosity evolution (till the so-called "ultimate" limit) with best forecast consequent integrated luminosity. Right: Integrated luminosity and running time to reduce by a factor two the statistical error based on flat luminosity (halving time). Superimposed the three long shutdowns and the area where we expect that radiation damage will call for changing of the low- $\beta$  quadrupole triplet (also called inner triplet).

# 1.2. The physics landscape for the luminosity upgrade of the LHC

As mentioned in the European Strategy of Particle Physics of 2006, the LHC upgrade depends critically on the physics motivations. It is difficult to quantify in rigorous terms the absolute return of a projected amount of integrated luminosity when we are dealing with a discovery facility, since the actual returns will depend on precisely what is found. The case of the Tevatron Run 2 provides a good example: if the Higgs boson had a mass of ~ 160 GeV, the available luminosity would have guaranteed its discovery, but about twice as much would

<sup>&</sup>lt;sup>1</sup> European Strategy for Particle Physics, <u>http://cern.ch/council/en/EuropeanStrategy/ESParticlePhysics.html</u>, adopted by the CERN Council at a special session at ministerial level in Lisbon in 2006.

<sup>&</sup>lt;sup>2</sup> European Strategy Forum for Research Infrastructures, ESFRI, <u>http://ec.europa.eu/research/esfri</u>

have been needed for a mass of 125 GeV. It is nevertheless remarkable that some of the most impressive results from Run 2, like  $B_s$  oscillations, the observation of single top production, the precision measurement of the top quark mass and others, were achieved after 20 years since the first Tevatron collider run. Tantalizing hints of new phenomena, like the production asymmetry of top quarks, have also emerged only after a major fraction of the ultimate luminosity sample was analysed. This is recognition of the scientific longevity of a hadron collider, and its potential to deliver surprises, provided a sufficiently rapid luminosity doubling time is attainable.

The discovery at the LHC of a resonance consistent with a Higgs boson of mass  $m_H \sim 125$  GeV, gives today a compelling and concrete case to define, quantify and justify the goals of the long-term LHC exploration. Having fixed the mass of the potential Higgs boson, its production and decay properties are now completely predicted, if it fits within the Standard Model (SM). In particular, the SM predicts that at  $m_H \sim 125$  GeV a large number of decay final states becomes accessible for exploration at the LHC, provided the integrated luminosity is large enough. An example is given by the decay modes such as  $H \rightarrow \mu^+\mu^-$  and  $H \rightarrow Z\gamma$ , which would be totally beyond reach if  $m_H$  were larger than ~150 GeV, but which at  $m_H \sim 125$  GeV can be detected and precisely measured with 3000 fb<sup>-1</sup>. The availability of a broad spectrum of production and decay modes will enable a broad range of cross checks of the consistency of the SM predictions with the actual measurements. New opportunities are now open also for the study of the Higgs self-interaction, a measurement that has always been deemed critically limited by the available luminosity and by the range of accessible Higgs decay modes.

The further probe the mechanism underlying the breaking of electroweak symmetry (EWSB), to prove that the new particle is indeed responsible for it, and to determine whether it is a fundamental particle (as predicted by the SM and other theories), or whether it is a composite object (as predicted by others), more measurements will be necessary. These include the determination of the W and Z self-couplings and the measurement of WW scattering at high energy. The former probes the weak-interactions' equivalent of the anomalous gyromagnetic factor of the muon, g–2, and the permille precision goal, necessary to test radiative corrections, can only be achieved at the LHC with the HL-LHC luminosities. The latter tests whether the Higgs boson is the sole responsible for the unitarization of WW scattering at high energy, or whether other new phenomena are present, indicative of a new strong dynamics underlying the EWSB mechanism and of a Higgs composite substructure. While the study of WW scattering would mostly benefit from an increase in the LHC beam energy, the HL-LHC luminosities will be necessary to perform the first tests ever of this very sensitive probe of EWSB and of the true nature of the Higgs boson.

Regardless of whether the new discovery is or not a SM Higgs boson, physicists anticipate the existence of new phenomena at the TeV scale, in order to address issues like the hierarchy problem or the existence of dark matter. In parallel with the discovery of a possible Higgs boson, the LHC experiments have by now set strong constraints on a large number of proposed scenarios of physics beyond the SM (BSM). For example, supersymmetric partners of quarks and gluons are ruled out in generic supersymmetric theories, if their mass is below ~1.5 TeV. While this leaves well open the possibility that they be discovered, at a higher mass, when the LHC reaches 14 TeV, at these large masses the production rates will be small, and high-statistics precision measurements of their properties will call for a luminosity well beyond the nominal LHC phase. Similar considerations apply to most of the other cases of BSM scenarios. For example, while new Z' gauge bosons, signalling the existence of new weak interactions, can be discovered with 300 fb<sup>-1</sup> up to 4-5 TeV, the full HL-LHC luminosity will be needed to determine their properties if their mass is above 2.5 TeV. Since the available LHC data constrain the existence of Z' bosons below 2.5 TeV, we can state already today that the clarification of any such discovery will need the luminosity upgrade. Existing studies also show that a tenfold increase in the LHC integrated luminosity will extend by 30-50% the discovery reach of new particles.

The first years of operation of the LHC experiments have shown that their performance matches, and often surpasses, the expectations. This is particularly true of the ability to operate in a regime of very high pile-up, a critical test for effective data taking in the HL-LHC environment. Likewise, the theoretical modelling of the properties of pp collisions at these energies has proven very accurate. These elements corroborate the projections made in the past for the physics potential of the HL-LHC phase, as reviewed above. If anything, they prove these projections to be over conservative, strongly suggesting that an increased ambition in terms of reach and precision is justified. The full exploitation of the physics programme outlined above requires progress on all fronts, from a reduction of the theoretical uncertainties that limit the precision of the data interpretation, to an improved performance of the detectors, to cope with such challenging conditions. Now that  $m_H$  is known, theoretical and experimental work can focus on the optimization of the tools.

The High Luminosity LHC project is working in close connection with the companion ATLAS and CMS upgrade projects of 2018-2023 and the upgrade foreseen in 2018 for both LHCb and Alice. This document will not discuss in further detail the physics reach, for which we refer to the reports being submitted by the individual collaborations, and is devoted the upgrade in luminosity of the LHC machine.

# 1.3. Objectives of the luminosity upgrade and relation to the LHC baseline programme.

# 1.3.1. HL-LHC goals

The LHC is designed for a 14 TeV collision energy, i.e. 7 TeV per proton beam, and a peak luminosity for each of the two general purpose experiments (ATLAS and CMS) of  $1 \times 10^{34}$  cm<sup>-2</sup>s<sup>-1</sup> (this value being called also nominal design luminosity). This luminosity associated with a bunch spacing of 25 ns (2808 bunches per beam) gives an average value of 27 event/crossing, or pile up.

**The main objective of High Luminosity LHC** 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  $5 \times 10^{34}$  cm<sup>-2</sup>s<sup>-1</sup> with levelling, allowing:
- 2) An integrated luminosity of **250 fb<sup>-1</sup>** per year, enabling the goal of **3000 fb<sup>-1</sup>** twelve years after the upgrade. This luminosity is about ten times the luminosity reach of the first twelve years of the LHC lifetime.

The above goal have been set with the companion LHC detector upgrade program, based on the hypothesis of 25 ns bunch spacing and an average pile up of  $\sim$  140.

# **1.3.2.** LHC luminosity and experience gained from present operation

Luminosity is, after collision energy, the most important parameter of a collider, because it is proportional to the number of useful events. For physics purposes, luminosity integrated over time is the relevant parameter: however integrated luminosity does not depend on collider

performance only, but also on many external parameters (injector performance, availability and quality of technical services, long stops or short breaks required by maintenances, etc.). The expectations in term of integrated luminosity of Fig. 1 are based on LHC capability and general run parameters (peak luminosity, burning rate of protons, duration of a run, etc.) and on the running experience at CERN, which includes the external factors previously mentioned. As a rule of thumb, it is estimated that LHC running at design peak luminosity of  $10^{34}$  cm<sup>-2</sup>s<sup>-1</sup> will produce about 40 fb<sup>-1</sup> of integrated luminosity per year for each of the two general purpose experiments, ATLAS and CMS.

As mentioned above, LHC is at present providing collisions at 8 TeV with proton beam energy of 4 TeV. A long shutdown (LS1) of about 20 months, is planned for 2013-14 to consolidate the splice at the magnet interconnects (the cause of the incident of September 2008). This intervention will allow **operating the magnets near the design value of 8.3 tesla (T)**, therefore enabling to reach collision **energy in the 13-14 TeV** range. However, during LS1 many interventions will be carried out in addition to the splice consolidation, like substitution of few electrically weak magnets and removal of limits to beam intensity (R2E or radiation to electronics effects, RF power system, etc). Once the intensity limit removed, and the design luminosity hopefully attained and passed in 2015, then in the years 2017-2020 LHC can run steadily "producing" luminosity and heading toward the so called "ultimate" design luminosity, which is about twice the nominal luminosity, i.e.,  $2.15 \times 10^{34}$  cm<sup>-2</sup>s<sup>-1</sup>. This ultimate luminosity performance was planned to be reached by increasing the bunch population from 1.15 to  $1.7 \times 10^{11}$  protons, with a bunch spacing of 25 ns (beam current increases from 0.58 A to 0.86 A).

Actually the performance of 2012 at 4 TeV beam energy is already potentially beyond the nominal design luminosity, when scaling is applied for 7 TeV beam energy. We run stable collisions at surprisingly high beam-beam tune shift values: value of  $\Delta Q_{b-b} > 0.03$  has been routinely reached, which is three times the prudent value of 0.01 taken for the nominal design LHC tune shift, and even a factor two beyond the value foreseen for "ultimate" design performance to be reached in a later stage of the machine. This favourable surprise has given the opportunity of using intense bunches with 1.5-1.6×10<sup>11</sup> protons/bunch spaced by 50 ns, instead of nominal 1.15×10<sup>11</sup> protons/bunch spaced by 25 ns, a solution that has come naturally because the luminosity depends quadratically on the bunch population and only linearly on the bunch number.

The (instantaneous) luminosity *L* can expressed as:

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

 $\gamma$  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 2808 for 25 ns

*N* is the bunch population. N <sub>nominal 25 ns</sub>:  $1.15 \times 10^{11}$  p ( $\Rightarrow 0.58$  A of beam current at 2808 bunches)

 $f_{rev}$  is the revolution frequency (11.2 kHz)

 $\beta^*$  is the beam beta function (focal length) at the collision point (nominal design 0.55 m)

 $\varepsilon_n$  is the transverse normalized emittance (nominal design: 3.75 µm)

*R* is a luminosity geometrical reduction factor (0.85 at 0.55 m of  $\beta^*$ , down to 0.5 at 0.25 m)

 $\theta_c$  is the full crossing angle between colliding beam (285 µrad as nominal design)

 $\sigma$ ,  $\sigma_z$  are the transverse and longitudinal r.m.s. size, respectively (16.7 µm and 7.55 cm)

The use of 50 ns spaced bunches avoids the regime of e-clouds, with a negligible time for scrubbing the beam pipe wall, while the use of the 25 ns would have required at least 2-3 weeks of beam scrubbing and conditioning, time that would have been missed for the physics. In addition to this, the lower than expected emittance delivered by the LHC injectors at 50 ns (by a factor two, partly foreseen as margin), could be well maintained and used in LHC: this has further enhanced the luminosity reach, making the 50 ns spacing a key ingredient of the today success of LHC, despite the more rapid decay of luminosity due to proton burning. However, also in this domain the positive news from LHC operation is that luminosity levelling is possible and actually easier than foreseen: levelling by just beam separation has been used already in 2011 for LHCb collision point (at relatively low luminosity). Despite of all this bias in favour of the 50 ns, the "nominal design" 25 ns scheme will be tested soon, to experimentally verify the scrubbing time needed to mitigate/suppress the e-cloud: if the tests are positive the 25 ns scheme will remain the LHC baseline, to be used after LS1. Indeed 50 ns with higher bunch population enhances the number of events per crossing, with a loss of quality of the data taking by the experiments which can be detrimental to the physics reach of the LHC.

# 1.3.3. Present luminosity limitations

There are various expected 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 (see next section 1.4). Mitigation of potential performance limitations arising from the LHC injector complex are addressed by the companion CERN project: LHC Injector Upgrade Project (LIU), which should be completed in 2018 (LS2). Any potential limitations coming from the LHC injector complex put aside, it is expected that the LHC will reach a performance limitation from the beam current, from cleaning efficiency at 350 MJ beam stored energy, from the beam-beam interactions with the designed operation mode at the ultimate bunch intensity of  $1.7 \times 10^{11}$  protons and from the acceptable pile-up level. Any further performance increase of the LHC will require significant hardware and beam parameter modifications with respect to the designed LHC configurations.

# 1.4. Enabling LHC operation till 2035 by Improving Consolidation

As above mentioned, the LHC performs extremely well in terms of luminosity. However, its astonishingly good performance should not hide the fact that LHC remains a very complex and somehow "fragile" machine, vulnerable to breakdown of various systems and wear out of many components. Many systems were not designed for best flexibility in operation: with the experience gained in the LHC construction and operation we do know, now, what is best. This goes well beyond the basic consolidation that is already going on for LHC, dedicated to reconstitute an adequate number of spare components, to enable safe and continuous operation with nominal parameters, and to complete systems that were partially removed in the LHC construction for lack of funding or time.

Before discussing the jump in performance due to a full upgrade, we therefore introduce the concept of "improving consolidation", i.e. a number of measures and interventions that just enable the LHC running continuously at its maximum performance with reasonable availability. We call it "improving" consolidation because we will not limit simply to anticipate breakdown or wear out of equipment: the interventions and equipment replacement will be designed to improve when possible peak performance and machine availability, which both concurs to integrated luminosity, and to increase flexibility and ease of repair and

maintenance, an important objective for a machine operating at 1000 times the beam stored energy and 50 to 100 times the luminosity of previous similar machine. The improving consolidation will allow reaching 800-1000 fb<sup>-1</sup>, more than doubling in the period 2023-2035 the luminosity reached in the 2010-2021 LHC run. Let's review the main equipment and systems that will need the pushed consolidation.

# 1.4.1. Magnets

As shown in Figure 2 right, at certain value of integrated luminosity we will enter in the radiation damage region. Collision debris are mainly intercepted by the low-beta quadrupole TAS and other absorbers. However a good fraction of them escapes and is absorbed inside the quadrupole cold mass of the low-beta triplets with two main effects: 1) heat deposition that may limit the performance of the superconducting magnets by increasing the conductor temperature; 2) radiation damage, especially to insulation but also to metallic components.

The first effect, heat deposition, put a limit on peak luminosity at about  $1.7 \ 10^{34}$ ; the uncertainty is estimated around 25%, probably in the conservative sense, so ultimate peak luminosity is still possible in the present configuration but not at all certain, based on this hardware limit.

The second effect, which just scales with the dose, and therefore with the integrated luminosity, calls for a replacement of the inner triplet. The quadrupoles may withstand 400-700 fb<sup>-1</sup> but some corrector magnets of nested type (a corrector package assembled inside the low-beta quadrupole cold mass) are likely to wear out already at 300 fb<sup>-1</sup> or less. Damage must be anticipated because the most likely way of failing is through sudden electric breakdown, entailing serious and long repairs. That's why replacement of the triplet must be envisaged before damage. Replacement of the low-beta triplet is a long intervention, requiring more than one year shutdown and must be coupled with a major detector upgrade. Furthermore the replacement must be coupled with improvement of the quadrupole aperture, to give room to an increase of the luminosity via lower  $\beta^*$ . Further, the whole Interaction Region (IR) zone needs to be redesigned with larger D1/D2 (the pair of recombination/separation dipoles), with a new DFBX, the cryo-distribution electrical feedbox of the low-beta triplet (considered today the most fragile of the critical equipment) and with much better access to various equipment for maintenance.

# 1.4.2. Cryogenics

An important consolidation of the LHC cryo-plant is adding a new helium refrigerator in the Point 4, to separate the cooling of the four LHC Superconducting RF modules from the magnet cooling circuit. The present coupling has two adverse effects: i) it greatly reduces the flexibility of intervention: any stop of cryogenics of the magnets halts the cryogenics of the RF and viceversa, which is detrimental to the machine availability and then to integrated lumi; ii) the triplet at left of P5 (CMS) is cooled by the refrigerator of P4, which has to cool not only an arc and a long straight section, like in the other LHC sector: here it has to cool also the RF cryomodules, reducing considerably the cooling power which is available for the triplet at Point 5 Left. When the machine will operate near nominal condition, the coupling may cripple the luminosity of P5 and also the operation with 25 ns bunch spacing (that requires more cooling power in the arcs because of the e-cloud heat load). It is foreseen to implement the new cryo-plant and the full separation between SCRF and Magnets cooling already in 2018 during LS2.

A further consolidation, that is deemed necessary in the long term, is the separation between the cooling of the inner triplets and few stand-alone superconducting magnets from the arc. This coupling means that an intervention in the triplet region requires warm up of the entire arc (an operation of 3 months, not without risk). When running at high luminosity and full energy this coupling will be detrimental to LHC availability. A full separation is the first necessary step, followed by a final consolidation with new cryo-plants, dedicated to the triplet region, to fully decouple the IR zone form the arc.

# 1.4.3. Collimation

The collimation system has been designed for the first phase of LHC life. Today it is operating very well, according to design. However the severe wear out by aging, imposed by beam impacts, will become more and more tough and will eventually require a complete renovation. However, this renovation must be done with new materials and new concepts to cope with higher than foreseen energy density of the LHC. As previously mentioned, one of the reasons of the very high performance of the LHC is a transverse emittance half the nominal value, which has an impact on the operation and wear of the collimation jaws, among the most delicate equipment of the whole LHC since they have to withstand the primary beam. All new collimators will be equipped with Beam Position Monitors ("button" collimators), in order to improve accuracy and time of setting up the jaws, and will be designed for a low impedance to make possible to increase the beam current and then luminosity. This consolidation will concern the momentum and betatron cleaning in P3 and P7, as well as the tertiary collimators protecting the triplets. Any small gain in triplet aperture and perforce must be accompanied by an adequate consolidation or modification of the collimation system.

A second area that will require a special attention to the collimation system is the Dispersion Suppressor (DS): here a leakage of off-momentum particle, into the first and second main superconducting dipole, has been already identified as a possible LHC performance limitation. Various concepts of collimation for the cold area (the DS is part of the continuous cryostat) have been studied. An international review called in 2011 has advised to postpone installation of this new collimation system in 2018, while supporting all necessary studies to well evaluate the problem for future LHC beam conditions and the associate R&D to identify the best solution. 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 room gained is sufficient for placing special collimators. This new 11 T dipole, which is developed in a collaboration CERN-Fermilab, might become the first magnet breaking the 10 T barrier in an accelerator. For the collimation system two options are under investigation: cryo-collimators operating at 20-60 K (with some features similar to the ones of the SIS100 FAIR project) and more classical room temperature collimators with a special, very compact, cold-warm-cold bypass. The system is likely necessary for ions, in IP2 DS, and most probably for IP1 and IP5 with luminosity above nominal. The actual need for P3 and P7, where we have the standard collimators that also generate off-momentum particles, is under assessment.

# 1.4.4. R2E and SC links for remote cold powering

Many electronics equipment of the LHC are vulnerable to single event upset, which is one of the most frequent causes of LHC unavailability, already at present energy and luminosity. A first consolidation plan is under way, profiting of annual Christmas breaks and of LS1. Among the most difficult equipment to cure for R2E are the magnet power converters. They are bulky equipment and further shielding is almost impossible. While a considerable effort is under way to study how to replace the radiation sensible electronic boards with rad-hard cards, another more radical solution is also pursued: removal of the power supplies and

associate DFBs (electrical feed-boxes, delicate equipment today in line with the continuous cryostat) on ground surface. This will solve radically the R2E problem of power converter and will make much easier all intervention on the electrical circuits: most of the intervention in the tunnel requires electrical consignation of the magnets and disconnection of the delicate HTS current leads; both operations will be possible at surface. Not only LHC availability will be greatly improved (because of less stop and much faster intervention, without tunnel access) but radiation dose to people will be lessened. Removal of all powers supplies at surface would be very expensive and almost impossible, so we have identified the region where R2E level is higher and where the ALARA principle requires this radical solution: the RRs alcoves of P7, IP1 and IP5 and the UJ alcoves of IP1 and IP5. Not surprising the high luminosity regions are most sensible to radiation, together with Point 7 where a set of 600 A power converters are placed in front the betatron cleaning collimators: in this particular case removal will be done in a lateral tunnel since here ground surface is not accessible.

Removal to ground surface is possible only thanks to a novel technology, not yet developed at the LHC design and construction: Superconducting links (SCLs) made out of HTS (YBCO or Bi-2223) or MgB<sub>2</sub> superconductors. The high operating temperature of these materials offers a large margin of stability, 100 to 1000 higher than classical Nb-Ti, and a wide temperature excursion, from 4 K to 20 K in case of the MgB<sub>2</sub> (favoured because of the much lower cost) and 4 to 40 K for HTS. SCLs will allow a 40 kA – 700 m long horizontal link in P7 and 200 kA – 300 m long in IP1 and IP5. The vertical jump is of course the 100 m of the LHC tunnel depth. Water cooled resistive cable are ruled out because of the dissipated power, 30 MW (40% of the total LHC power consumption) and because they would require new power converters of much higher power than the present ones.

# 1.4.5. **QPS**, Machine protection and Remote manipulation

Other systems will need vigorous consolidation to assure the LHC running for long time in condition between nominal and ultimate luminosity, i.e., collecting between 40 and 80 fb<sup>-1</sup>. Even without the HL-LHC jump in luminosity of 250 fb<sup>-1</sup>/y, just running at 80 fb<sup>-1</sup>/y will not be possible in the present LHC without a vigorous consolidation.

The first system requiring consolidation is the *Quench Protection System* of the superconducting magnets. Based on a design of almost twenty year ago, it lacks flexibility to face operating conditions somehow different than foreseen. Here just a few examples: i) make the QPS fully redundant also in case of power loss; ii) introduce low energy discharge on quench heaters, to avoid premature aging of the quench heaters, among the most fragile components of the superconducting magnets; iii) easy adaption of the detection thresholds: it turned out that for various reasons a number of magnets demand a threshold which is higher than the standard one and that different operative conditions required different thresholds; iiii) interlocking the quench heater discharge with a sensor of quench heater integrity, to avoid dangerous short circuits which may cause event similar to the LHC incident of 2008 (despite the many mitigation measures, the stop would be probably several months). In general the QPS will need a complete revamping around 2020.

*Machine protection*: improving vulnerability to kickers sparks and asynchronous dumps. The kicker system is, with collimation, the main barrier against severe beam induced damage. The system today is at its limit and will need modification and improvement to guarantee a probability of accident as low as  $10^{-5}$  to  $10^{-4}$ . Continuous renovation simply is not sufficient and we see already signs of necessity of renovation with improvements (extra heating),

especially in the injection system. Not only the kicker system, but also the interlock system needs to be fully renovated at around 2020.

*Remote manipulation*: LHC has not been designed specifically for remote handling. However the level of activation from 2020, and even earlier, requires a carefully study and development of special equipment to allow replacing collimators, magnets, vacuum components etc., according to ALARA principle. The first challenge will be the substitution of collimators; another big challenge will be the replacement of the inner triplet magnets and associated cryogenics and vacuum equipment. The higher the luminosity, the higher the necessity of interventions and the less the time operators can stay in contact with this equipment. While full robotics is difficult to implement, given the real conditions, remote manipulation and supervision is the key to minimize the radiation dose to operators.

# 2. Upgrading the performance to the High Luminosity LHC goals

# 2.1. Luminosity levelling and virtual peak luminosity

Both consideration of energy deposition by collision debris in the interaction region magnets, and 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 Fig.1.3 left, the luminosity profile without levelling quickly decreases from the initial peak value, due to "proton burning" (protons lost in collision). By designing the collider to operate with a constant luminosity, i.e. "levelling" it and suppressing its decay for a good part of the fill, the average luminosity is almost the same as the one of a run without levelling, see Fig 1.3 right, however with the advantage that the maximum peak luminosity is only a fraction.

Indeed pile-up and degraded performance by intense radiation are serious limitations in the high luminosity regime: coping with peak luminosity higher than  $5 \times 10^{34}$  cm<sup>-2</sup> s<sup>-1</sup> may become impossible and therefore levelling has become a key ingredient of the HL-LHC baseline.



Figure 2.3: Left: luminosity profile for a single long run starting at nominal peak luminosity (black line), with upgrade no levelling (red line) with levelling (dotted line). Right: luminosity profile with optimized run time, without and with levelling (blue and red dashed lines), and average luminosity in both cases (solid lines).

The concept of luminosity levelling introduces a new parameter: the virtual peak luminosity, i.e. the luminosity that could be "virtually" reached at the beginning of the run without levelling. Levelling means acting on one or more of the parameters controlling the (instantaneous) luminosity: by detuning the chosen parameter(s) the luminosity is kept fixed at the chosen levelled value. Then the same parameters(s) is slowly retuned to its ideal value

in a way that the gain just compensates the proton burn-off due to collisions (and potential other phenomena decreasing the luminosity, like beam losses, emittance increase etc.). It is clear from this reasoning and from Fig 1.3 that the higher the virtual luminosity, the longer the collider can be operated at constant levelled luminosity. The ratio k = Virtual Peak *Lumi/Levelled Lumi* is therefore one of the parameter to be maximized in the HL-LHC configuration.

Once all the parameters are fully retuned to compensate the proton burning (and other possible effects) the luminosity by definition decrease with time since levelling is not anymore possible, as shown in Fig. 1.3, until the run is terminated to restart another luminosity cycle.

# 2.2. Integrated luminosity and availability

The upgrade has one main objective: an integrated luminosity, proportional to the discovery potential, to be reached in a "reasonable" time: 3000 fb<sup>-1</sup> in 10-12 years. This fixes the goal of annual integral lumi to 250 fb<sup>-1</sup> (300 fb<sup>-1</sup> will be pursued, if possible). The fact that the maximum levelled luminosity is limited, means that to maximize the integrated value one needs to maximize the run length, which can be obtained by filling the maximum number of proton, i.e. by maximizing the beam current:  $I_{beam} = n_b \times N$ . Other key factors for maximizing the integrated luminosity are a short average machine turnaround time (we assume 5 hours in the following), the optimization of the luminosity decay time in a run (se Fig. 1.4) and the overall machine efficiency. With HL-LHC parameters, the cycle depicted in Fig. 1.4 can yield more than 3 fb<sup>-1</sup>/day! However, the HL-LHC will not always perform as in Fig 1.4. Some runs will be prematurely aborted, with beam dump required by BLM spikes and equipment failures, either true or spurious. And any equipment failure during the machine turnaround might entail a longer than anticipated turnaround time (time from end of physics to physics again, all included). In certain cases extra time is required to solve problems, for tunnel access or for the cryogenic system recovery. All this can be summarized in the overall machine "efficiency" defined as the ratio between actual time spent in physics production and the physics time of the ideal cycle. In practice in a lumi levelled operation this is the same as the ratio between actual integrated luminosity and integrated lumi obtained with a continuous ideal cycle.

HL-LHC with 150 days of physics needs an efficiency of ca. 40%. During 2011 run the efficiency varied, without lumi levelling, between 20 and 40%. Clearly for the integrated lumi the efficiency counts almost as much as the virtual peak performance. Requiring an efficiency much higher than the one of the present LHC, with a (levelled) luminosity five times the nominal one, and with beam current larger than ultimate (see next section), will be a real challenge.

The issue of efficiency calls for a further challenge: we need not only increasing the peak performance, but also decreasing the downtime by reducing the number of faults and by mitigating their impact on the machine availability. For this reason the project must foresee a vigorous consolidation for the high intensity and high lumi regime and must increase the reliability of all systems: in one word,

# the High Luminosty LHC must be, also, a High Availability LHC



Figure 1.4. Luminosity cycle for HL-LHC with levelling and a short decay (optimized for integrated lumi). The set of parameters generating cycle are the 25 ns column of the table 1, stretched.

# 2.3. Upgrade parameters

# 2.3.1. Bunch spacing

Although the 25 ns bunch spacing remains the baseline, given the experience of the first years of operation, 50 ns is kept as a viable alternative, in case the e-cloud or other unforeseen effects undermine the 25 ns performance. However, the companion LHC detector upgrade project is designing for an average pile up around 140: for 25 ns spacing this means about  $5 \cdot 10^{34}$  of luminosity, while at 50 ns this means limiting the levelling luminosity to half, if the pile up has to be the same. This translates into a longer run time for the 50 ns and inevitably for a request of even higher efficiency, unless higher pile up can be accepted (new concepts like pile density per volume are being explored to overcome absolute pile limitation). Experience with LHC shows that the best set of parameters for actual operation is difficult to predict. An upgrade should provide the potentiality of performance over a wide range of parameters, and eventually the machine and experiments will find the practical best set of parameters in actual operations.

# 2.3.2. Beam current

The total beam current may be a hard limit in the LHC since many systems are affected by this parameter in a direct way: RF power system and RF cavity, Collimation, Cryogenics, Kickers, Vacuum, beam diagnostics, etc., and other systems in an indirect way, mainly through an increase of the R2E events, like quench detection system of the SC magnets, and virtually all controllers.

Radiation effect put aside, all systems have been designed in principle for  $I_{beam}$ = 0.86 A, the so called "ultimate" beam current. However this is still 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. In principle we should be able to do so, profiting from the margin of some systems and better than designed performance (for example, the cryostat insulation losses). The LHC operation in 2015-17 at full beam energy and at beam current pushed above nominal 0.58 A, will tell us the actual margin we do have on  $I_{beam}$ . As a general consideration one can state

that 50 ns bunch spacing is a little better since for the same peak luminosity it requires a factor  $\sqrt{2}$  less beam current than 25 ns. However this translates inevitably in a  $\sqrt{2}$  less proton circulating in the machine and inevitably in a shorter levelling time, which requires a higher efficiency to maintain the target value of integrated luminosity.

# 2.3.3. Emittance and bunch population

Transverse emittance is already better than design, thanks to better than anticipated performance of injectors, their transfer lines and good emittance preservation in the LHC. Together with the absence of a beam-beam limit, the advantage offered by low emittance favours the 50 ns bunch spacing over the 25 ns, since the beam splitting in the injectors is half. Indeed emittance is better than expected for both 25 and 50 ns, however the gain is accentuated for 50 ns. For HL-LHC it is needed to increase the beam brightness, which is a property that must be maximized at beginning of the beam generation and then preserved throughout the entire injector chain and LHC itself, i.e. it is a global property. The LIU project has as primary objective to increase the brightness at the LHC injection, basically increasing the number of protons per bunch by a factor two above what we have today while keeping the emittance at the present low value. It is worth noticing that for the injectors the 50 ns stretched goal (Table 1) is the most difficult scenario to comply with (assuming that the e-cloud effects in the SPS, which are more accentuated for the 25 ns, can be mitigated).

# 2.3.4. $\beta^*$ and cancelling the reduction factor R

A classical route to the luminosity upgrade is to reduce  $\beta^*$  by means of stronger and larger aperture low- $\beta$  triplet quadrupoles. With respect to reducing the emittance, this is a local action, rather than a modification of the whole machine and injector chain. The conventional approach to a triplet upgrade is to keep the overall triplet length constant which leads to an increase of the peak field in the quadrupole magnets when increasing the aperture at constant gradient. However, a new design approach has been chosen for the HL-LHC upgrade: reducing the gradient of the triplet magnets which allows a larger magnet aperture for a given peak field but also increases the overall triplet length and the maximum beam size in the triplet magnets. The combination of gradient and of length strongly depends on the maximum allowable peak field, quite different for different superconducting technologies. However a reduction in  $\beta^*$  value implies an increase of beam sizes and a wider crossing angle, to limit the long range beam-beam (LRbb) effects: a wider crossing angle requires larger aperture triplet magnets, a larger D1 (first separation/recombination dipole) and a few modifications in the matching section, too. Stronger chromatic aberrations coming from the larger  $\beta$ -functions inside the triplet magnets may exceed the strength of the correction circuits. Such peak betafunction is also and mainly limited by the possibility to match the optics to the regular beta functions of the arcs. A previous study has shown that in LHC a practical limit is  $\beta^* = 30-40$ cm, from the 55 cm foreseen in nominal operation. However a novel scheme has been recently proposed to overcome the limitation of LHC matching section. The scheme called Achromatic Telescopic Squeeze (ATS) uses the adjacent arcs as enhanced matching section and the increase of the beta-functions in those arcs to boost at constant strength the efficiency of the lattice sextupoles which perform the chromatic correction of the triplet. In this way a  $\beta^*$ value of 15 cm can be envisaged and a flat optics with a  $\beta^*$  as low as 5 cm in the plane perpendicular to the crossing plane is enabled. Actually, a  $\beta^*=10$  cm has been recently attained in a machine development run dedicated to test the ATS principle. For the  $\beta^*$ reduction the quadrupole needs to double the aperture, with a peak field 50% above the present LHC, requiring a new superconducting technology based on Nb<sub>3</sub>Sn (see section on technical challenge).

The drawback of very small  $\beta^*$  is that it requires larger crossing angle, which entails a reduction of the R geometrical factor, see luminosity expression. In Fig. 1.5 the reduction factor is plotted vs.  $\beta^*$  values. To restore the full gain given by low  $\beta^*$ , we have two options:

- 1. reduce the beam separation at the parasitic encounters: for this calculation we take a safe  $11\sigma$  separation; however a preliminary test in 2012 not yet conclusive has shown that 7-8 $\sigma$  separation might be acceptable and even beneficial by slowly cleaning away the halo particles)
- 2. Compensate the LRbb by electric wire. This solution is under study but is not yet fully proved.

Probably a mix of the two can be a viable solution, however the most efficient and elegant solution for compensating the geometric reduction factor is the use of Crab Cavities.



Figure 1.5 : Behaviour of geometrical reduction factor of luminosity vs.  $\beta^*$  with indicated two operating points: nominal LHC and HL-LHC. The sketch of bunch crossing shows the reduction mechanism.

Special RF "crab" cavities are capable to generate transverse electric field are used to give a torque to the beam. In this way the beams do not suffer from overlap reduction due to  $\theta_c$ , as shown in fig. 1.5: a crab cavity just rotates each bunch by  $\theta_c/2$ , such as they collides head on, overlapping perfectly at the collision point, see Fig. 1.6. In this way the crossing angle is maintained over the long drift space in the common vacuum beam pipe avoiding the LRbb inteeractions, but the geometrical reduction is totally suppressed. Of course the same opposite kick must be given to the beam at the opposite side of the collision point. Crab cavities have been successfully tested for the first time in the e<sup>+</sup>e<sup>-</sup> ring Belle at KEK, however their feasibility for hadron beam has still to be demonstrated. Crab cavities make accessible the full performance reach of the small  $\beta^*$  that ATS scheme and the large inner triplet quadrupoles can generate: their primary function is boosting the virtual peak luminosity for attaining the full HL-LHC performance. However they are thought to be also an easy tool for levelling, since by changing the voltage is straightforward to control the beam rotation and then the instantaneous luminosity.



Figure 1.6: effect of the crab cavity on the beam (small arrows indicate the torque on the beam by transverse varying RF field).

#### 2.3.5. Table of HL-LHC parameters

In Table 1 are listed the main parameters for the LHC upgrade in luminosity. For convenience, first are listed the nominal LHC operating parameters, then the upgrade parameters both for 25 ns and for 50 ns bunch spacing. As mentioned 25 ns is our operation target, the 50 ns being a fall-back solution. For both bunch spacing we quote two lists: baseline and stretched parameters, these last being the most ambitious objectives that might enable 300 fb<sup>-1</sup> per year. The efficiency (last line) is quoted for a goal of 250 fb<sup>-1</sup>/y. The efficiency of LHC in 2012 after the initial period is above 40%, so the efficiency proposed for the 25 ns is reasonable, nevertheless a big leap forward is required on increasing availability (as previously mentioned) and turnaround time (time from end of physics to next start of physics). The 50 ns option requires an efficiency level that is not realistic. For this reason for 50 ns we need to explore the new concept of pile up density, as mentioned in 2.3.1, and diluting the events per crossing over a longer and larger cylindrical space enclosing the overlap of the encountering beam overlap. A measure that can help to reach the goal at 50 ns, and help for 25 ns, is increasing the number of day for proton physics: in table 1 we assume 150 days: maybe this number can be increased to 180-200, at expense of ion runs and of machine development allocated time. A margin that is not considered in the table is the possibility to work at  $\beta^*$  of 10 cm, which thanks to the ATS and larger Nb<sub>3</sub>Sn quadrupoles should be within reach.

Parameter	Nom.	Stretched	Stretched	Baseline	Baseline
	25 ns	25 ns	50 ns	25 ns	50 ns
$N_{b} [10^{11}]$	1.15	2.2	3.5	2.0	3.3
n <sub>b</sub>	2808	2808	1404	2808	1404
I [A]	0.56	1.12	0.89	1.02	0.84
θc [µrad]	300	590	590	590	590
β* [m]	0.55	0.15	0.15	0.15	0.15
ε <sub>n</sub> [μm]	3.75	2.5	3.0	2.5	3.0
$\epsilon_s [eV s]$	2.5	2.5	2.5	2.5	2.5
IBS hor [h]	111	15	14	16	15
IBS long [h]	65	21	16	22	17
Piwinski	0.68	3.12	2.85	3.12	2.85
R red.fact.	0.81	0.31	0.33	0.31	0.33
b-b/IP[10 <sup>-3</sup> ]	3.1	3.3	4.7	3	4.5

Table 1 : parameters for HL-LHC compared with LHC nominal (in bold the most critical ones).

L <sub>peak</sub> (no crab)	1	7.4	8.5	5.3	7.6
Crabbing	no	yes	yes	yes	yes
L <sub>peak virtual</sub>	1	24	26	20	23
Lumi level	=	5	2.5	5	2.5
Pileup L <sub>lev</sub> =5L <sub>0</sub>	19(27)	140	140	140	140
Eff. <sup>†</sup> 150 days	=	0.59	0.98	0.63	1.0

# 2.4. Hardware modifications and challenges of HL-LHC

In this section we review the hardware that needs to be modified, rebuilt, or completely changed for the HL-LHC. In all cases, with the notable exception of the crab cavities, this new hardware is very much entangled with the improving consolidation plan reviewed in the section **1.4**.

While the LHC has been the summit of 30 years of hadron colliders evolution, its high luminosity upgrade will open the gate for new technologies and new concepts that will likely mark the next generation of colliders, either for hadrons or for leptons.



Figure 2.7: Schematic of the LHC, indicating the points of beam collision or beam services (P1 to P8). HL-LHC will requires deep modifications of 1.2 km of the accelerator in P1, P5, P2, P4 and maybe in P3 and P7.

# 2.4.1. Magnets in the Interaction Regions and Matching Sections

The present LHC constitutes the summit of 30 years of development in the domain of superconducting technologies: Nb-Ti based magnets are pushed to their limits: very compact two-in-one magnets provide 8.3 T operating field by using superfluid helium cooling (magnets are designed, and many have been tested, up to 9 T). The plot in Fig. 1.8 illustrates

the progress over the years from the resistive magnet era. The upgrade heavily relies on the success of the advanced Nb<sub>3</sub>Sn technology, since Nb-Ti superconductor cannot go beyond 9 T. Nb<sub>3</sub>Sn has been under development for more than ten years and has now reached a maturity that allows designs of real equipment based on it. Nb<sub>3</sub>Sn has been used in solenoids for NMR spectroscopy for more than 20 years. ITER is now using Nb<sub>3</sub>Sn on a very large scale, 400 tonnes (similar to LHC scale), making a decisive step in industrializing the process. However, for accelerators we need a current density between 2.5 and 3 times that used in the ITER's toroidal coil. A 12-year-long programme led by DOE in the US and two EU programmes (FP6 CARE-NED and the current FP7-EuCARD) have shown the feasibility of Nb<sub>3</sub>Sn accelerator magnets with the proper qualities. In particular the US LARP (LHC Accelerator Research Program) has successfully tested a quadrupole that is already a step beyond the present LHC triplet quadrupole. For HL-LHC the Nb<sub>3</sub>Sn magnet inventory is: sixteen 8-9 m-long magnets for the IRs in P1 and P5; ten 11 T, 11 m-long dipoles for the Dispersion suppressors in P2, P1 and P5 (and may be P3 and P7). In addition we need ten D1/D2 recombination dipoles and four to eight Matching Sections Quadrupoles (all in P1 and P5) that can be made with well-known Nb-Ti technology: however they will have larger aperture and higher radiation dose, therefore they will be more challenging than the LHC magnets.

 $Nb_3Sn$  has also a higher temperature margin than Nb-Ti, therefore making easier dealing with heat deposition issue. The field quality is still a factor two worse than Nb-Ti but is steadily improving: last prototypes have, nearly, collider quality. The cost of the superconductor remains much higher than Nb-Ti but the total cost of the system, also considering a less demanding cryogenics, is only about 50% higher.



Figure 1.8: Progress of accelerator magnets for hadron colliders: from 2 to 9 tesla is the realm of Nb-Ti; beyond 9 tesla, Nb<sub>3</sub>Sn is needed.

#### 2.4.2. Crab Cavities

Superconducting (SC) RF cavities of large sizes (with f = 400 MHz), and based on Nb coated Cu technology developed for LEP, are employed in the LHC. The Crab Cavities for LHC will go beyond the state-of-the art for two reasons. The first is that the transverse cavity dimensions are limited by the 194 mm distance of the second beam, a value smaller that  $\lambda/4$  of 400 MHz wave, practically excluding the well-known geometry of an elliptical cavity: this calls for an unconventional, compact design. The second reason is the demand for very exact control of the phase of the RF (to better than 0.001°), since the slightest phase error would not only offset the bunch head and tail as required for head-on collisions with a non-zero crossing angle, but also the centre of the bunches, which for the very small transverse size of

the bunches would lead to an offset of the entire bunch and thus to a significant luminosity loss. For the accelerating cavities, a special region around Point 4 was created, see Fig. 1.7, in which the beam separation is increased, by the use of magnetic doglegs, to 400 mm in order to allow the installation of the elliptical 400 MHz accelerating cavities. Compact Crab Cavities could be installed on either side of each high luminosity Points 1 and 5, without additional doglegs, but their design would definitely be beyond the present state-of-the-art of SCRF cavity design. Fig. 1.9 shows by how much smaller the Compact Crab Cavity has to be than a conventional TM110 cavity, in order to fit between the LHC beam separation. The challenging requirement to the precise phase control is equally beyond the state-of-the-art, but similar requirements are found in modern XFEL light sources (like the one under construction in the APS upgrade of Argonne) and in next generation linear colliders. Of large concern are the failure modes of the Crab Cavities, which must be studied in detail in order to allow safe operation of the machine.

As mitigation scheme, would the crab cavity not be usable in LHC, is to collide flat beams at the smallest possible crossing angle, by pushing the compensating wires for the LRbb interactions.



Figure 2.9: Size of a typical  $TM_{110}$  cavity vs. its resonance frequency, indicating the requirements of a Compact Crab Cavity to fit between the LHC beam pipes without a dogleg.

# 2.4.3. Collimators

Safe handling of a beam of 1 A or more, with beta function at collision beyond the design value will also constitute a progression into new territory. For beam collimation, 75 collimators need to be precisely aligned in a dynamic mode with a precision of ~ 10  $\mu$ m, in order to assure the protection of the triplet against a beam that will have energy ~ GJ, something that is more than five times the present limit. The protection of the triplet must be accomplished during the large change of the collision beam parameter ( $\beta^*$  passing from 10 m to 10-15 cm), which will be one of the most critical phases of HL-LHC operation; just the beam halo itself could be well beyond the damage limit. Since the collimation system must be renovated anyway, the full upgrade performance is basically a request of more precise and more powerful material collimators.

# 2.4.4. Cryogenics and SC links for remote cold powering

Just to cope with higher heat deposition from the higher luminosity points, we would need dedicated power plant. In additions we would need to remove far away the magnet power converter. These two measures are already mentioned in the improving consolidation. The

additional performance, beyond the improving consolidation, that are requested both by cryogenic plants and by SC links for the full upgrade are technically important but are just above marginal in term of cost, complexity and time schedule. In particular with higher luminosity, and consequent more heat in the cold magnets, and the cooling of SC crab cavity at 1.9 K, the power of the new cryo-plant in P1 and P5 is in the 10 kW range, while for an improving consolidation a 5 kW should suffice. For SC links the difference is mainly in the total current, which is about 150 kA for the full upgrade of the power converters in the UJ alcoves (and may be limited to 60-70 kA for the improving consolidation). However the 200 kA SC link for the RRs alcoves will remain unchanged.

# 2.5. Project Plan and Cost

The performance of the HL-LHC run both in case of "only" improving consolidation and in case of full performance upgrade, can be summarized in the following graphs of Fig. 1.10. The integrated luminosity (right plot) is based on <u>optimist assumptions</u> of 90 fb<sup>-1</sup>/y in case of improving consolidation and of 300 fb<sup>-1</sup>/y for full performance upgrade.



Figure 1.10. Left graph: peak luminosity for LHC with improving consolidation (diamonds) and with HL-LHC full performance (square markers). Right graph: the same for the integrated luminosity.

In the same conditions and hypothesis we plot in Fig. 1.11 the halving time (i.e., the time to half the statistical error) and the doubling time, i.e. the time to double the statistics.



Figure 1.11 Halving time and doubling time for the LHC with improving consolidation and for HL-LHC with full performance.

The Cost-to-Completion of the full HL-LHC project amount to about 840 MCHF for Material (CERN accounting) and requires a little more than 1000 FTE-y, from 2012 to 2023 included. The split among improving consolidation and full performance is about 55%-45%, while the cost of personnel the improving consolidation will requires about 80% of the manpower for the full performance. In Figure 1.12 the required expenditure profile is reported.



Fig. 1.12. Cost in M+P (CERN accounting, cost of person is about 200 kCHF/y) for the HL-LHC project in the two configurations: profile vs. time.

In the following Table 2 the summary of the cost is reported.

	Improving Consolidation	Full performance	Total HL-LHC
Mat. (MCHF)	476	360	836
Pers. (MCHF)	182	31	213
Pers. (FTE-y)	910	160	1070
TOT (MCHF)	658	391	1,049

Table 2. Summary of the cost of HL-LHC with split between Consolidation and full performance.