

THE LARGE HADRON COLLIDER OF CERN AND THE ROADMAP TOWARD HIGHER PERFORMANCE

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Abstract: The Large Hadron Collider is exploring the new frontier of particle physics. It is the largest and most ambitious scientific instrument ever built and 100 years after the Rutherford experiment it continues that tradition of “smashing atoms” to unveil the secret of the infinitely small. LHC makes use of all what we learnt in 40 years of hadron colliders, in particular of ISR and Sp-pbarS at CERN and Tevatron at Fermilab, and it is based on Superconductivity, discovered also 100 years ago. Designing, developing the technology, building and finally commissioning the LHC took more than twenty years. While LHC is now successfully running, we are already preparing the future for the next step. First, by increasing of a factor five the LHC luminosity in ten years from now, and then by increasing its energy by a factor two or more, on the horizon of the next twenty years. These LHC upgrades, in luminosity and energy, will be the super-exploitation of the CERN infrastructure and is the best investment that the HEP community can make in order to extend the boundary of our knowledge at an affordable cost.

1- Introduction: Centennial of Superconductivity and Accelerators

On April 8 of 1911, K. H. Onnes and co-workers first observed the disappearance of electrical resistivity, in a sample of highly purified mercury. Onnes achieved this result because he was a great instrument maker: the first ten year after he took the chair of experimental Physics in Leiden he did not produce a single paper, concentrating his energy and will in founding and developing a school for the education and training of young technicians, and in developing the instrument for one of the most exciting adventures of physics at the end of XIX century: the race toward absolute zero temperature. Onnes specialized in gas refrigeration and in using it to test a key theory, the electrical conduction in metal. He first liquefied Oxygen (90 K) in 1894, lost to Dewar the race for Hydrogen liquefaction (20 K) but then won the most difficult one when he first liquefied helium at 4.2 K in 1908. This allowed him to carry out new fundamental experiments on electrical conduction. In 1911 he not only observed the “resistance almost nul” (Kes, 2011) but – thanks to the unique skills of the team he formed with patient work over many years – he was able to repeat the experiment three times that same year. Eventually, after having collected enough statistics he was able to state that what was happening was not what he expected: resistance was not going to zero smoothly when temperature was approaching zero; rather it passes through a sharp transition into a new phase that he called later superconductivity.

Onnes talked openly of a possibility to realize ten tesla magnets, only to be deceived soon after when he discovered that superconductivity was destroyed by small field of less than 50 mT. It was only in the 1970s, when the availability of modern alloyed superconductors like Nb-Ti made type II multifilamentary wires possible, that the race toward high fields really started. From then on the

destiny of the accelerator was signed (Wilson, 1999): SuperConductivity (SC) became the choice of preference for accelerators, as illustrated in Figure 1.

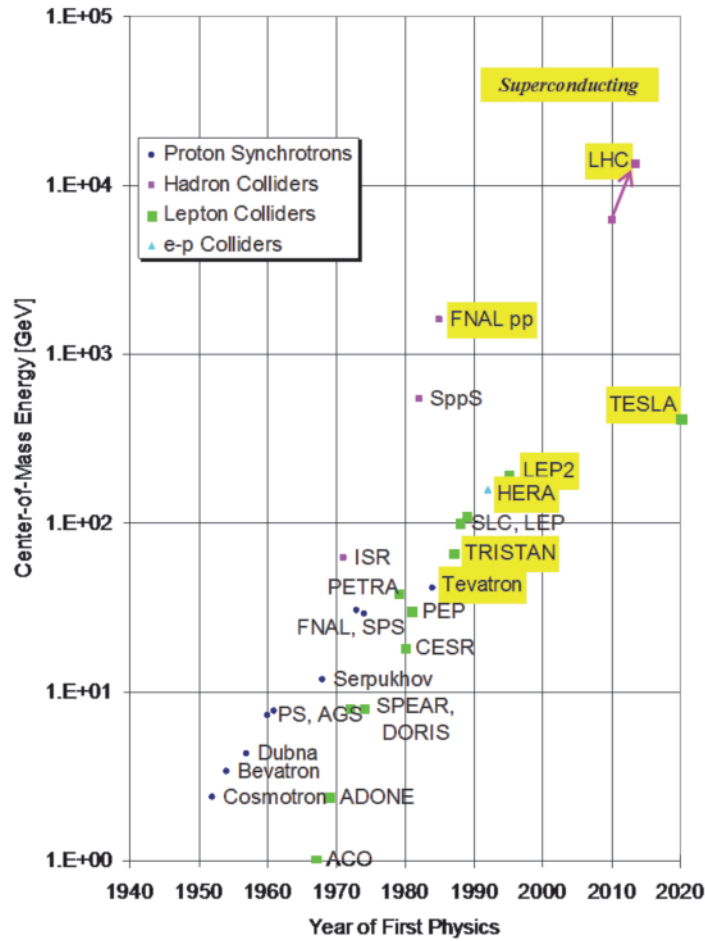


Figure 1. Evolution of accelerators with those making use of superconductivity highlighted in yellow

2- The advance of superconducting hadron accelerators and LHC early R&D

2.1 Early times and Tevatron

Hadron colliders have been at the forefront of Physics since the ISR in the 1970s. They can provide very intense beam and luminosity at the highest energy. When superconductivity was emerging in the seventies a project, called Isabelle and later CBa (Colliding Beam Accelerator) was developing SC magnets for a 2x200 TeV proton collider. Some delays and then the attempt to increase SC magnet field to 5 T troubled the project in the critical moment. Meanwhile in 1982 Rubbia et al. discovered the field particles W and Z at the CERN SPS, transformed for the purpose into a p-pbar collider. These factors contributed to the stop of Isabelle, favouring the start of the SSC project design. Meanwhile the construction of the Fermilab Tevatron, a machine to be installed in the tunnel of the Main Ring and meant to double its energy to 1 TeV/beam by means of 4.5 T superconducting magnets (Tollenstrup, 1979), was progressing with full steam. Much like the CERN p-pbar collider, the Tevatron was able to accommodate two counter-circulating beams of protons and antiprotons in

the same vacuum pipe, providing collisions at 2 TeV center-of-mass energy (Edwards, 1985). The Tevatron, inaugurated in 1983 at reduced energy, was made possible by the vision of Fermilab founder and director Robert R. Wilson, who stubbornly fought for it (eventually at the price of an early retirement as the condition to move on with the project), offering the first large application of superconductivity. This in turn kept Fermilab primacy of the energy frontier for more than 25 years.

2.2 HERA

The success of Tevatron, which was the first superconducting accelerator and the first very large superconducting system, paved the ground for a similar project in Europe, HERA, and for the “superproject”: SSC, the Superconducting SuperCollider in the USA. HERA, more or less the size of Tevatron, had the goal to collide a 0.8 TeV proton beam against a 30 GeV electron beam. The main contribution of HERA dipoles to the technology advancement was the use of a cold iron yoke (Wolff, 1988) while Tevatron magnets had a warm iron yoke. Tevatron made the choice of warm iron in order to minimize the time of warm-up and cool-down, and then the dead time for physics. However, following the good operation experience of Tevatron and HERA, all projects after 1985 were designed with cold iron, which make much easier force containment and alignment. HERA dipoles also employed aluminium collars, rather than stainless steel like the Tevatron dipole, to benefit from the larger thermal contraction of aluminium during cooling. HERA came into operation at 4.7 T in 1989, eventually reaching 5.5 T for 0.92 TeV proton beam energy about ten years later.

2.3 SSC

In the meantime a large R&D effort was going on in the USA for SSC. Based on 6.6 tesla magnets, SSC was constituted of two independent rings in a tunnel with a circumference of 87 km length, sited in Texas. For a decade, up to its cancellation by Congress on 21 October 1993, SSC was the cradle of main developments of SC technology for accelerators. The critical current density of Nb-Ti was raised to more than 3000 A/mm² at 5 T and 4.2 K, while the size of the Nb-Ti filaments was reduced to 5-6 μm to limit magnetization effects; Nb-Ti ingots were produced with high homogeneity and clad by a 4-6% Nb sheath, to prevent formation of brittle intermetallic compounds and improve performance and yield. Superconducting cable technology and QA made great progress. Studies of the magnet field quality were pursued systematically as well as new insulation technologies. New magnet designs were worked out: Two-in-One design (to host the two rings in one magnet), superferric magnets (for low cost and longer accelerators), partitioning the coils into different electrical circuits; all these new ideas came during these times. However, the project overall made slow progress, given the resources and the enormous intellectual effort. The management also under-evaluated LHC progress: despite use of a circumference three times smaller than that of SSC (CERN was bound to use the ring excavated to host the LEP machine), LHC was promising to reach the same physics performance, thanks to higher field magnets – which could partially compensate for the smaller ring – and to higher luminosity (LHC Study Group, 1991). LHC also profited from the great advances made for the SSC and made some winning choices. For example, the Two-in-One design, proposed for SSC but never accepted by the management, was picked up by LHC and brought to perfection with the LHC Twin Dipole (Perin, 1991). In Figure 2 the cross sections of the dipole magnets for the principal hadron colliders are shown.

DIPOLE MAGNETS

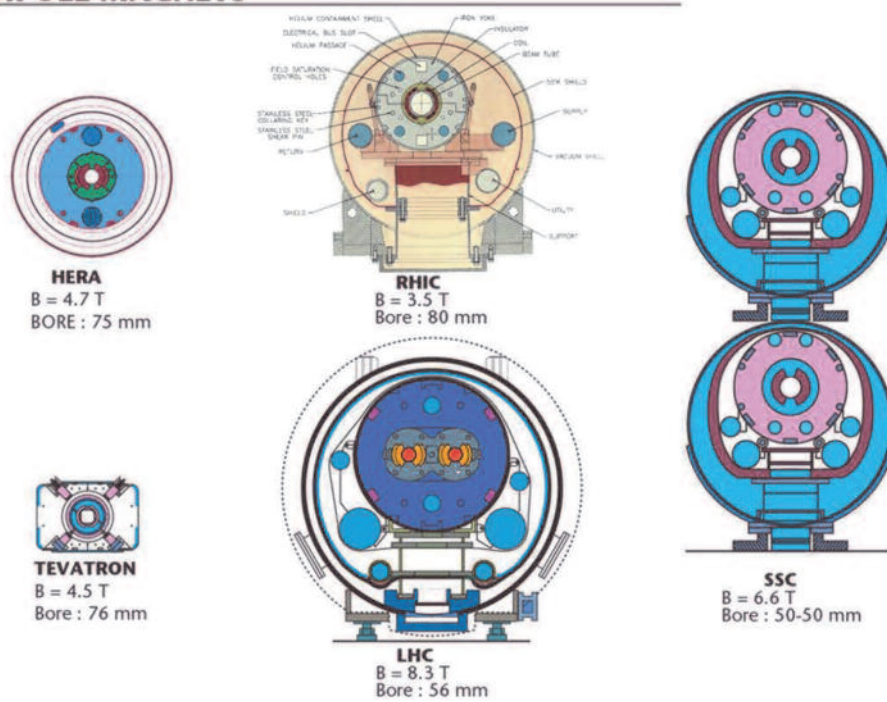


Figure 2. Comparison of dipoles from the Tevatron to the LHC.

2.4 The early R&D for LHC

The CERN strategy for the superconductor development was to concentrate on specific LHC issues - the dynamic effect due to the wide cable, the critical current optimization at 1.9 K and development of Helium cryogenics - and to rely on the SSC's advances for the other issues. There is indeed a large debt that CERN owes to the SSC project for the superconductor development (Rossi, 2011, Cern Courier).

A CERN development was proving the Two-in-One concept in long magnets and a superfluid helium cryostat. This involved assembling two superconducting coils from the HERA dipole production, which had ended in 1988, in a single cold mass and cryostat, the Twin Aperture Prototype (TAP). The magnet was successfully tested in 1990, reaching 5.7 T at 4.2 K, and 7.3-8.2 T at 1.8 K and thus supporting the choices both of the Two-in-One magnet design, and of the superfluid helium cooling.

In the same period, 1987-1990, the LHC dipole was designed, featuring an extreme variant of the Two-in-One: the "Twin" concept, where the two coil apertures are fully coupled, i.e., with no iron between the two magnetic channels. We now take this design for granted, but at the time there was scepticism within the community (especially across the Atlantic), as it was supposed to be much more vulnerable to perturbations because of the coupling and of an irresolvable (at that time) issue with field quality. However CERN defended this design with great resilience, as among other things it also made an important 15% saving in the cost.

The result of the first sets of twin 1 m long magnets came in 1991-92 and the field reached was well over 9 T, only 5-10% less than expected from the so-called "short sample" (the theoretical maximum inferred by measuring the properties of a short 50-70 cm length of the superconducting cable);

accelerator magnets normally work at 80%, or less, of the short-sample value. The results of the 1-m LHC models also made it clear that the cable's mechanical and electrical characteristics and the field quality of the magnet, both during ramp and at the flat top, were not far from the quality required for the LHC. The final step of the R&D toward LHC was to manufacture 10 m long magnets of the twin design to demonstrate that full-size, LHC dipoles of the final design were feasible.

In 1988 and 1989, in the wake of a long term effort on superconducting technology for accelerators launched by Prof. Zichichi at beginning of the '80s, the Italian INFN signed a collaboration with CERN for a special contribution to LHC R&D. INFN then launched the design and manufacture of LHC-type superconducting cables for long magnets (Acerbi et al., 1992) and in 1989 ordered two 10 m long twin dipoles from Ansaldo Componenti (Italy). INFN followed this job through LASA, a new lab devoted to applied superconductivity for accelerators, a further heritage of the superconductor development program of INFN President Zichichi. The development of the superconductors was pursued in LASA first by means of a National project (a Cyclotron built in Milan and later installed at INFN-LNS of Catania) and then through a strong participation to the HERA project (about 240 superconducting dipoles for the accelerator and the large thin superconducting solenoid of ZEUS detector). The LASA laboratory became one of the main collaborating institutes of CERN for the LHC project. Parallel to the INFN effort, the French CEA-Saclay Laboratory, DAPNIA department, took over the design and construction of the first two full-size superconducting quadrupoles for the LHC. The engagement of CEA-Saclay on the LHC quadrupoles continued throughout the duration of the project, as a special French contribution to LHC construction.

In 1993 the LHC project had to pass through a tough review devoted to the cryo-magnet system, led by Robert Aymar, who as CERN's director-general 10 years later would harvest the fruit of the review. With the review over and completion of the long magnet prototypes approaching, the credibility of the LHC project increased. In autumn 1993, the SSC came to a halt - certainly because of high and increasing cost (more than \$12 billion) and the low economic cycle in America, but also because the LHC now seemed a credible alternative to reach similar goals at a much lower cost (\$2 billion in CERN accounting). Rubbia, near the end of his mandate as director-general, led the project without rival. In a symbolic coincidence, the demise of the SSC occurred at the same time as leadership of the LHC project passed from Giorgio Brianti, who had led the project firmly from its birth through the years of uncertainty, to Lyn Evans, who was to be in charge until completion 15 years later. The end of the SSC and the green light for the LHC was marked by the delivery to CERN of the first INFN dipole magnet in December 1993, just in time to be shown to the Council. This was followed four months later by the second INFN magnet and then by the CERN magnets as well as by the two quadrupoles designed and built by CEA.

Returning to the first dipole, see Figure 3, it was tested in time for a very special April session of the Council in 1994. The magnet passed with flying colours, going above the operational field of 8.4 T at the first quench, beyond 9 T in two quenches, and a first quench above 9 T after a thermal cycle i.e. full memory. The excellent performance was actually misleading, giving the idea that the construction of LHC might be easy. In fact it took a long period of six years before another magnet as good as that one was again on the CERN test bench. However, the other 10 m long magnets performed reasonably well and with the two excellent CEA quadrupoles (3.5 m long), CERN was able to set up the first LHC magnet string, to test it thoroughly and finally receive the first official

approval of the project in December 1994, still with a missing magnet scheme to be amended at end of 1996 when USA and Japan special contributions were secured.

Many other formidable challenges were still to be resolved both on the technical side and on the managerial and financial side. The technical issues included the non-uniformity of quench results and the problem of retraining that plagued the second generation of LHC prototypes, the unresolved question of the inter-strand resistance, the change of aluminium for austenitic steel as the material for the collars and the lengthening of the magnets from 10 m to 15 m with the consequent curvature of the cold mass. Looking back at the decade 1985-1995 when the base for the LHC was established, it is clear that a big leap forward was accomplished during this period. The vision initiated by Robert Wilson for the Tevatron was brought to fruition, pushing the limit of Nb-Ti to its extreme on a very large scale. New superconducting cables, new superconducting magnet architectures and new cooling schemes were also put to the test, in the constant search for economic solutions that would be applicable later to large scale production.



Figure 3. First LHC dipole (collaboration CERN-INFN) on the test bench in April 1994.

3- Performance of LHC and ten year plan

From the early prototypes of 1995 to the end of hardware commissioning about 13 year passed, comprising long years of industrialization, construction and installation (Evans, 2007, Rossi, 2007, Evans and Bryant, 2008, Evans, 2009). LHC beam first circulated on 10th September 2008, only to be stopped nine days later by the very serious incident caused by a faulty magnet interconnection (Rossi, 2009). It took more than fourteen months to repair and recommissioning the accelerator. On 29th November 2009 beam was circulating again and quickly gained the record beam energy. From 30th March 2010 the machine is operating at 3.5 TeV/beam (half the design value) and at 50 ns bunch spacing.

The machine has since then performed remarkably well with a steady increase in luminosity at a pace that has been a rather good surprise (Lamont, 2011). The progress of luminosity so far is plotted in Fig. 4.

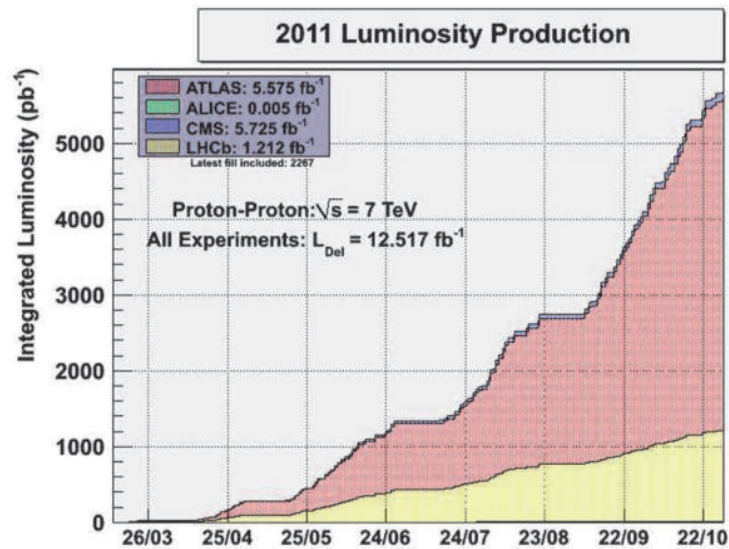


Figure 4. LHC integrated luminosity in 2011. For comparison in 2010 it was 50 pb^{-1} , i.e., 5 times less than the difference between ATLAS and CMS integrated luminosity in this graph.

The reasons for such a success are manifold and in general can be traced back to clever design, to careful construction and to unprecedented readiness in commissioning and operation. Some specific points are listed below:

- The magnetic machine is more stable and reproducible than expected. The field quality of the magnets is excellent and the aperture is considerably larger than anticipated.
- The head-on beam-beam limit is at least a factor 2 higher than anticipated. Actually a few runs at tune shift of $\Delta Q = 0.023$ have been performed with acceptable beam losses. The long-range beam-beam encounters, which are today limited by the 50 ns beam structure, well fits the simulations, giving hope that they can be controlled and limited for 25 ns spacing.
- For the 50 ns bunch spacing the emittance preservation in the injector chain and through LHC injection and acceleration is much better than anticipated. Furthermore, the single bunch population limit in the injector chain and namely in the SPS is higher than expected.
- With better than expected minimum beam lifetime, the present collimation system is capable to protect the beam up to nominal current and more: actually if the extrapolation of a recent experiment will be confirmed, the ultimate current (0.86A) can be fed into the ring without quenching the superconducting magnets.

The LHC long term plan, see Fig. 5, foresees a first Long Shutdown in 2013-14, LS1, mainly intended to consolidate the defective splices in between magnets. This long term plan ends with the project High Luminosity LHC (HL-LHC). A few equipment items requested for the HL-LHC project will be put in place in LS1, like installation of the Long Range beam-beam compensation wires and some civil

works in IP1 and IP5 and P7 related to SC links. A second Long Shutdown, LS2, which is today foreseen in 2018, will feature a number of equipment installations in the tunnel in view of the high luminosity, specifically addressing intensity limitations: 1) collimation in the cold arc coupled with novel technology 11 T twin dipoles; 2) installation of a new cryo-plant to decouple the SC magnet arc and IR from SCRF for sector 3-4, removing present low- β limitations on the left side of the CMS; 3) installation of LR b-b wires (and/or electron lenses) in all points; 4) SC links installation for removing some power converters from radiation sensible zones; 5) civil engineering work and infrastructure for the hardware to be installed in 2022; 6) installation of a crab cavity prototype to study its behaviour in LHC. These activities will be complemented by the interventions for upgrading the injectors: a) connection of Linac4 to the LHC chain; b) upgrade from 1.4 to 2 GeV of the PS Booster; c) removal of e-cloud limitations and 200 MHz RF upgrade in the SPS, etc. Finally, the third Long Shutdown LS3 in 2022-23 will be dedicated to the main hardware installation for the HL-LHC run.

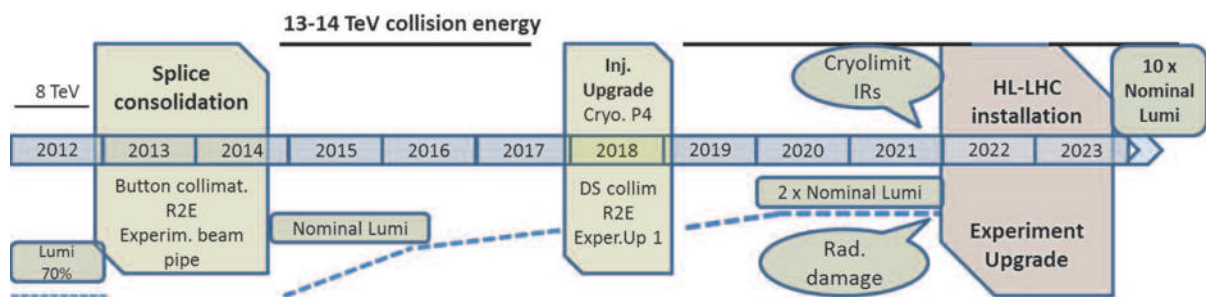


Figure 5. LHC plan for the next ten years, with the main interventions and increase of energy and luminosity indicated.

4- LHC luminosity upgrade

Based on the previous assumptions the integrated luminosity until LS3 is plotted in Fig. 6, where the region of radiation damage to triplet magnets is shown to be reached around 2021. In addition the time to half the statistical error on the physics data is also reported (halving time). Both main indicators for the timing of the upgrade, radiation damage and halving-time well above 10 years, call for the upgrade right after 2020, very consistent with the assumed timing of LS3.

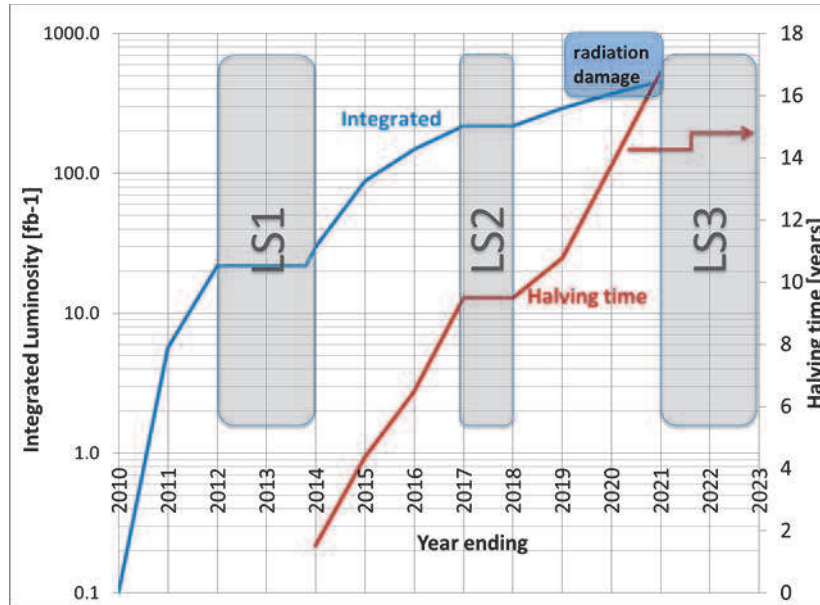


Figure 6. Evolution of LHC integrated luminosity in the next ten years. The time of running to half the statistical errors is also plotted vs. time.

The main goal of the HL-LHC has been set: to reach 3000 fb^{-1} of accumulated luminosity in 10-12 years after the upgrade while “limiting” the maximum peak luminosity to $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to limit the experimental pile-up (Rossi, 2011, IPAC). This implies automatically that the peak luminosity must be very near to the average luminosity in the run, i.e. the luminosity levelling is strictly necessary. Levelling means having a virtual luminosity at the beginning of the run (L_{peak}) much higher than the levelled luminosity (L_{lev}): however the instantaneous lumi is kept at the – lower – levelling value by “detuning” from optimal value one (or more) of the parameters controlling the lumi itself. This parameter is then slowly “retuned” toward its optimal value to compensate the protons lost in nuclear collisions (proton burning). Levelling has been already tested in 2011 in the LHCb experiment (IP8) at $L_{\text{lev}} = 3.2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ by varying the vertical beam separation.

Luminosity levelling is very attractive because it limits the pile-up in the experiment, reducing the technical difficulty and cost of the detector upgrade and limiting the power deposited in the magnetic elements of the IRs (Interaction Region) and of the DS (Dispersion Suppressor).

The classical formula for luminosity for the LHC conditions (short bunches, equal round beams) reads:

$$L = \gamma \frac{f_{\text{rev}} n_b N_b^2}{4\pi \varepsilon_n \beta^*} R \quad R = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^*} \gamma\right)^2}}$$

γ being the relativistic factor, n_b the number of bunches, N_b the bunch population, ε_n the normalized transverse emittance, β^* the beta function at beam crossing, θ_c the full crossing angle and R the geometric reduction factor.

In Fig. 7 a few parameter sets for HL-LHC are reported with minimum separation for parasitic beam-beam encounters of 10σ (L is in unit of $L_0=10^{34} \text{ cm}^{-2} \text{ s}^{-1}$). The parameter set of column 2 should produce the ideal luminosity cycle and the integrated luminosity evolution plotted in Fig. 7, with an

efficiency of 60% (in LHC at present it is less than 40%). In bold are the “pushed” parameters and in red the ones that are considered very difficult or dubious. As mentioned before we use the new parameter space opened by $\Delta Q_{\text{beam-beam}}=0.02\div 0.03$ (with full compensation of the long-range beam-beam tune shift) and by injected brightness twice the initial design (Bruning, 2011). Also we assume a beam current around 1.1 A (impacting on cryogenics, RF, collimation, beam losses, beam dump, machine protection, ...) and β^* as low as 15 cm thanks to the ATS scheme (Fartoukh, 2011) that produces β_{peak} of 20 km in the triplet and enhances the chromatic correction capability of the machine. We assume attaining the required gradient and aperture in the low- β quads (with Nb₃Sn technology) and to use crab cavities both to fully cancel the geometric reduction factor and as luminosity levelling tool.

Efficiency is defined as the ratio between the annual luminosity target of 250 fb⁻¹ over the potential luminosity that can be reached with an ideal cycle run time with no stop for 150 days: $t_{\text{run}} = t_{\text{lev}} + t_{\text{dec}} + t_{\text{turn}}$. The turnaround time after a beam dump is taken as 5 hours, t_{decay} is 3 h while t_{lev} depends on the total beam current

Parameter	Nom.	Target	Target	LIU	LIU
	25 ns	25 ns	50 ns	25 ns	50 ns
N _b [10 ¹¹]	1.15	2.0	3.3	1.7	2.5
n _b	2808	2808	1404	2808	1404
I [A]	0.56	1.02	0.84	0.86	0.64
θ _c [μrad]	300	475	445	480	430
β* [m]	0.55	0.15	0.15	0.15	0.15
ε _n [μm]	3.75	2.5	2.0	2.5	2.0
ε _s [eV s]	2.5	2.5	2.5	2.5	2.5
IBS h [h]	111	25	17	25	10
IBS l [h]	65	21	14	21	11
Piwinski	0.68	2.5	2.5	2.56	2.56
F red. fact.	0.81	0.37	0.37	0.37	0.36
b-b/IP[10 ⁻³]	3.1	3.9	5	3	5.6
L _{peak}	1	7.4	8.4	5.3	7.2
Crabbing	no	yes	yes	yes	yes
L _{peak virtual}	1	20	22.7	14.3	19.5
Pileup L _{lev} =5L ₀	19	141	257	137	274
Eff. 150 days	=	0.62	0.61	0.66	0.67

Figure 7. The parameter table of HL-LHC. The main target is the central one (target 25 ns spacing). In bold the main parameters that critically determine the upgraded performance.

5- LHC energy upgrade

The luminosity upgrade is a major step but it might not be the last one for the LHC tunnel. Indeed a study on a possible energy upgrade of the LHC, called High Energy LHC (HE-LHC) has been launched (Todesco and Zimmermann, 2011). The feasibility of such a machine critically depends upon achieving magnetic fields twice higher than the LHC. First studies have indicated that there is no show stopper for a HE-LHC. In particular the synchrotron power, passing from 0.17 W/m-beam in LHC to 2.8 W/m-beam in the HE-LHC, may be dealt with a beam screen operating around 60 K, a value still reasonable for vacuum. The maximum energy goal of the HE-LHC has been set to 33 TeV collision energy. The 16.5 TeV/beam can be reached by dipole field around 20 T, with a 2/3 filling factor as in the present LHC ring. HE-LHC magnets are the natural evolution of the one needed for HL-LHC, see Fig. 8, where the big leap forward in magnet technology needed for the upgrades is well depicted.

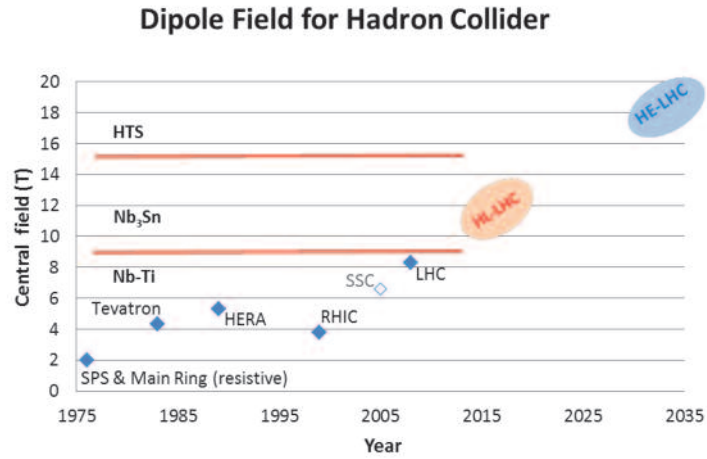


Figure 8. Evolution in time of the field of dipole magnets for hadron colliders, indicating the time scale and filed level for the LHC upgrades in Luminosity and Energy.

At levels beyond 15 tesla, the magnetic structure become complicated, given the stored energy and forces that are five time the present LHC level! A possible lay-out of the magnet cross section is shown in Fig. 9: the lay-out is based on rectangular coil blocks rather than classical $\cos\theta$ shape and needs to use all type of existing superconductors: Nb-Ti for the 0-8 T coils, Nb₃Sn for the 8-16 T coils and HTS for the 16-20 T coils. The cost of such a 20 T dipole is about three times the present LHC dipole. Indeed the magnetic system would be 80% of the cost of the entire machine, estimated at about 6,000 MCHF with a very crude approximation. The cost can be reduced considerably with a field of 15-16 T, rather than 20 T: in such a case Nb₃Sn technology will be sufficient without using expensive and still-far-from-being-developed HTS cables. However, in such a case the energy of the collider would be “limited” at 27 TeV in the centre of mass.

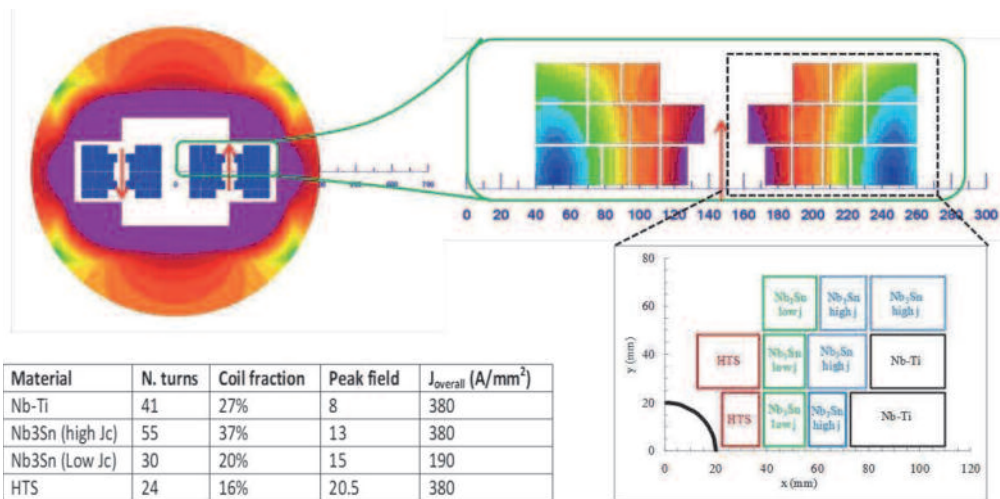


Figure 9. Cross section of a 20 T dipole magnet for the HE-LHC. Top left: full cross section (800 mm of diameter of the iron yoke); top right: expansion of one quadrant of the coils, showing the bloc structure. Bottom right: further expansion of the right half of the coil quadrant, with indicated the various SC material employed in

each single coil bloc. In the bottom left table the percentage of the different SC material is indicated. Arrows indicate magnetic field.

Other beam dynamics issues for HE-LHC appear not more difficult than LHC itself, thanks also to the excellent beam damping time of 2 hours (26 hours in the LHC). Also collimation seems not more difficult than the HL-LHC case since the beam power and power density will not increase. HE-LHC relies on injection energy > 1 TeV (0.45 TeV in LHC) to permit a small magnet aperture: 40 mm (56 mm in LHC), a critical issue to attaining 20 T. The 1 TeV injection calls for an upgrade of the present SPS, called SPS+. The main magnet needed for such machine would be very similar to the one already under development by the GSI-INFN collaboration for FAIR-SIS300 (Fabbricatore, 2011): maximum field of 4.5 T, 1T/s of field ramp rate. The magnet model, full cross section and 3 m of length, is already built and test is just under way. The advantage of SPS+ is the saving of a good fraction of the 70 MW of today's SPS consumption and the possibility of providing a 2 MW beam to LAGUNA experiment for neutrino search with a machine that is anyway needed for the LHC upgrade program.

For HE-LHC many issues need to be addressed more deeply: one is quadrupole strength and the best lattice optimization since quadrupole gradients cannot be doubled as "easily" as dipole field. In addition to the main magnets possible critical points are the beam injection and extraction. In particular the beam dump with beam rigidity more than double and the more or less the same space allocated for the kickers looks problematic, but not impossible.

HE-LHC is certainly a very difficult machine but it is also a "saving" machine with continuity, making re-use of all existing infrastructure of CERN, and is one of the main options for the future of CERN and High Energy Physics. In any case the main technology for the HE relies on the advance already on going for the HL-LHC, plus a specific development on HTS that is just starting. In about four years we believe that the energy reach of HE-LHC can be finally assessed, allowing determining its physics reach, the design and construction issues as well as its cost with a reasonable accuracy.

6- Conclusions

LHC is the pinnacle of more than thirty years of hadron collider development. Superconductivity, discovered just 100 year ago, has been the choice of preference for HEP accelerators since the Tevatron and possibly will also be the workhorse for the future. The roadmap for the future foresees a luminosity upgrade in ten years from now, to extend the physics reach of the present machine. Based on 12 tesla magnets, the luminosity upgrade is the ideal "preparatory phase" for a much more ambitious project, the LHC energy upgrade (Bottura et al, 2012). Meant to reach between 27÷33 TeV c.o.m. collision energy, the High Energy LHC will be the ultimate exploitation of the LHC tunnel. It requires an extensive R&D on SC magnets, which must reach 16 to 20 Tesla field in operation. R&D must be carried out in this decade in the shadow of the HL-LHC construction, in this way HE-LHC could be installed in around 2035, i.e., after the collection of 3000 fb⁻¹ of integrated luminosity at LHC energy. Beyond HE-LHC energy, a new larger circumference tunnel would be necessary for attaining even higher energy, or new technology like plasma acceleration must be pursued.

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