LHC LUMINOSITY AND ENERGY UPGRADE*

W. Scandale#, CERN, Geneva, Switzerland

Abstract

LHC upgrade studies are ongoing as part of the EU CARE-HHH and of the US-LARP programmes. The aim is a ten-fold increase of the LHC luminosity by the middle of next decade, a possible upgrade of the injector complex to inject at 1 TeV and, at a later stage, to raise the collider energy. The motivations for the LHC upgrade are discussed. An overview of beam dynamics and technological challenges is presented. Preferred scenarios to maximize the integrated luminosity and the physics reach are identified.

MOTIVATIONS

The LHC under completion at CERN will start soon and gradually reach the nominal luminosity and beyond. In Table 1 the beam parameters for nominal and ultimate performance are shown [1], together with two upgrade modes, discussed later.

Table 1: LHC parameter and performance.

Parameter [units]	Nominal	Ultimate	Short bunch	Long bunch
No. of bunches n_b	2808	2808	5616	936
$p^+ \times$ bunch N_b [10^{11}]	1.15	1.7	1.7	6.0
bunch spacing Δt_{sep} [ns]	25	25	12.5	75
beam current [A]	0.58	0.86	1.72	1.0
E_{beam} [MJ]	366	541	1085	631
Beta at IP β* [m]	0.55	0.50	0.25	0.25
Full xing angle θ_c [μrad]	285	315	445	430
Piwinski ratio $\theta_c \sigma_s/(2\sigma^*)$	0.64	0.75	0.75	2.8
L lifetime τ_L [h]	15	10	6.5	4.5
L_{peak} [10^{34}cm^{-2}s^{-1}]	1.0	2.3	9.2	8.9
$T_{turnaround}$ [h]	10	10	5	5
Events per Xing	19.2	44.2	88	510
$\int_{\text{one year}} L\, dt$ [fb^{-1}]	66.2	131	560	410

Different forecasts can be made on the evolution of the LHC performance. Up to six years may be required to reach the full potentiality, also in consideration of the staged installation of collimators and dilution kickers in the beam disposal system, of the planned RF upgrade and of the progressive cleaning of the vacuum pipe. One can imagine being able to reach the nominal luminosity in four years and then to ramp-up to the ultimate luminosity $L = 2.3\times10^{34}$ cm^{-2}s^{-1} in another couple of years. One can assume more pessimistically to reach $L = 1.0\times10^{34}$ cm^{-2}s^{-1} in four years and then to be stuck for some reason, such as current limitation, in a performance plateau. Fig. 1 shows predictions for both cases. Thick lines represent the cumulated luminosity and thin lines the forecasted run-time to multiply by four the number of the previously cumulated experimental data, thereby halving the statistical errors. Both the optimistic scenario to ultimate performance (larger slope curves), and the case limited to nominal performance (smaller slope curves) are shown.

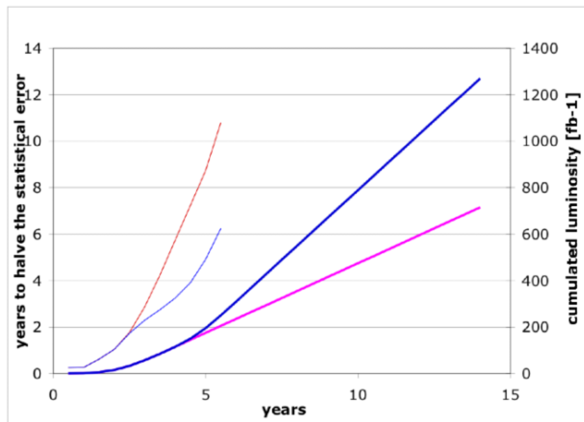

Figure 1: Cumulated luminosity (thicker lines, right scale) and forecasted run-time to halve the statistical errors (thinner lines, left scale).

The run-time halving the statistical errors is a steep function of time, assuming large values after few years of operation. In these conditions, increasing the available data set becomes a painfully slow process and controlling the systematic error of the experimental apparatus is a non-trivial issue. With the increase of the cumulated luminosity, the integrated dose due to collision debris will slowly induce radiation damages, reducing the triplet magnet lifetime and the accelerator reliability. The damage threshold, which in a conservative assumption corresponds to an integrated luminosity of 700 fb^{-1}, will be eventually reached in about ten years. Indeed, in less than a decade of exploitation the initial LHC potential may well be fully reached and the interest of the experimenters may start declining. To extend the LHC lifetime beyond the middle of the next decade one should identify the future accelerator needs and launch a substantial improvement programme. Should the nominal and then the ultimate luminosity be reached much earlier than predicted, i.e. in four years instead of six, the previous conclusion will become even more stringent. Both the run-time for halving the errors and the cumulated luminosity will increase faster than in Fig. 1

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#walter.scandale@cern.ch

and the motivation for launching the upgrade plans will become certainly stronger.

INCREASE OF THE LUMINOSITY

The luminosity upgrade scenario should aim at a substantial increase of the physics reach both in Atlas and CMS by the middle of next decade. This implies maximizing the reliability of the accelerator complex, including the injector chain, and reaching the highest peak luminosity compatible with machine protection and radiation damages. In this perspective, the crucial tasks are three: consolidating the existing accelerators, proposing scenarios for the highest beam performance and launching R & D plans for future improvements.

PS and SPS magnet consolidation programme

The PS and SPS main magnets have already shown clear signs of aging induced by the combined effect of mechanical fatigue, corrosion, irradiation and limited preventive maintenance. A consolidation programme of the PS dipoles has been launched and will be pursued in the next decade until completion of the refurbishment. A similar plan is being devised for the SPS magnets and the necessary investigations to decide the most appropriate actions have been launched. As an intermediate step, the decision has been to keep as small as possible the energy and the duration of the SPS flat top during the fixed-target operation to mitigate the effect of thermal and magnetic stresses. In due time the consolidation will be extended to the entire injector chain, to reduce the potential sources of beam downtime and guarantee the prompt availability of the injectors for a minimal turnaround time and a maximal integrated luminosity.

Limitations of the injector complex

The injector complex (Linac2, PSB, PS and SPS) is not optimized to fill the LHC with the highest intensity, highest density beams. With the foreseen injection scheme [2] today one can only deliver the nominal beam at 450 GeV, but not yet the ultimate beam [3]. Various limitations have been identified. The space charge during the 50 MeV injection in the PSB is one of them. A remedy is to build the new Linac4 delivering H^- ions at 160 MeV, thus halving space charge forces in the PSB injected beam [4]. This will also allow injecting in the PS a single PSB shot, which can be immediately accelerated, thereby reducing the LHC filling time. So far, the nominal LHC bunch population depends on SPS performance limitations at 450 GeV. Predictions for ultimate LHC intensity are based on scaling and need experimental confirmation. The vertical single bunch instability due to electron cloud will make it difficult to increase the transverse beam density beyond the nominal value. The transverse mode-coupling instability could also limit the LHC intensity. The extraction kickers have been identified as a source of transverse impedance, which should be reduced as much as possible. Preliminary studies have already shown that significant improvements should be expected when pushing the SPS injection energy in the range of 40-60 GeV, instead of 26 GeV, and the LHC injection energy in the range of 1 TeV [5].

Upgrade of the LHC ring

The optimal path for the LHC luminosity upgrade should include the increase of beam current and the modification of the two high luminosity insertion regions (Atlas & CMS). Limiting factors can be found from the inspection of the explicit formula of the luminosity:

$$L = \frac{N_b{}^2 n_b f \gamma}{4\pi\varepsilon_n \beta^*} F, \quad F = 1 \Bigg/ \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2} \; ,$$

where N_b is the bunch population, n_b the number of bunches per beam, f the revolution frequency, γ the relativistic factor, ε_n the normalized transverse emittance and β^* the betatronic function at the Interaction Point (IP). The full crossing angle θ_c introduces the geometric factor F by which the luminosity is reduced, σ^* and σ_z being respectively the transverse and the longitudinal rms beam size at the IP. The factor $\gamma/4\pi\beta^*$ depends on the beam energy and on the focussing strength of the insertion. Its natural limit is imposed by the maximum dipole field and by maximum gradient of the Interaction Region (IR) quadrupoles. The factor N/ε^* represents the transverse beam density which is mainly limited by the maximum tolerable head-on beam-beam effect, of the order of a few 10^{-3} in relative units of the betatron frequency shift. It is also strongly influenced by the space charge limit in the injector chain and by the various dilution factors after each transfer from an accelerator to the next. The factor $N_b n_b f$ is proportional to the single beam current, limited by the long range beam-beam effect, by the collective instabilities threshold, by the synchrotron radiation power which can be absorbed by the beam screen and by the maximum stored beam energy which can be dissipated in the beam dump system. These considerations clarify why many of the LHC hardware components have a strong influence on the maximum achievable luminosity.

The luminosity upgrade should proceed in steps. The first step consists in reducing β^* from 0.5 m to 0.25 m. The corresponding peak luminosity increases by a factor two, provided the bunch length is halved by means of a new RF system and the crossing angle is increased by a factor $\sqrt{2}$, to keep the same relative beam separation d/σ at the parasitic collision points, measured in terms of the local value σ of rms beam size. This scenario, corresponding to the short bunch case of Table 1, is the safest in terms of beam dynamics, machine protection, and radiation risks, but the new IR magnets are challenging. Further increases in luminosity involve other major modifications of LHC and of the injector chain to exceed the ultimate beam intensity and possibly to inject around 1 TeV. Key parameters to be modified and the interplay between them are shown in Fig. 2, where the drawn hyperbolic curves represent operational modes with the same circulating current [6].

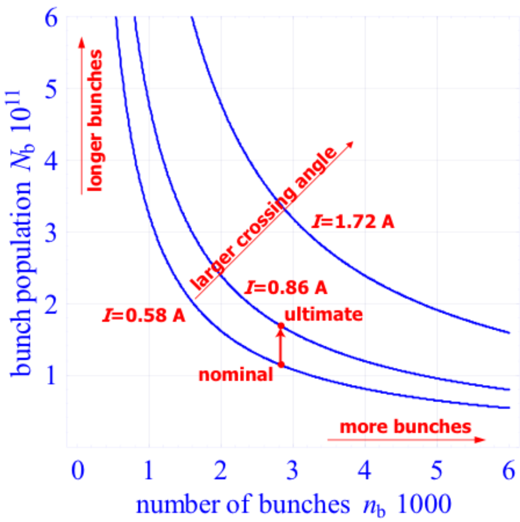

Figure 2: Beam parameters to upgrade performance.

The peak luminosity at the beam-beam limit depends on the ratio I/ε^*, where the total beam intensity I is limited by the injectors, by electron cloud effects and by collimation and machine protection in the LHC. The crossing angle depends on the beam intensity and is limited by the triplet aperture. If the injectors can provide a higher brightness N_b/ε^*, longer bunches will allow increasing luminosity without exceeding the beam-beam limit. Longer bunches will also guarantee less electron cloud and RF heating effects. However the event pile-up in the physics detectors increases with the bunch population N_b and colliding more bunches with shorter bunch spacing is therefore the preferred option for the experiments. A spacing of 12.5 ns is presently favoured by the experiments and would yield a peak luminosity of 9.2×10^{34} $cm^{-2}s^{-1}$, while a multiple of 5 ns, such as 10 or 15 ns, is preferable for the accelerators. However, the short bunch option may be incompatible with electron cloud and long-range beam-beam effects and with a safe cleaning and machine protection. For instance, recent computer simulations have shown that the e-cloud related heat load is an order of magnitude larger than in the nominal case and imposes a drastic and expensive upgrade of the cryogenic system [7].

At the "burn-off" limit, when the beam lifetime is dominated by nuclear p-p collisions, the only way to increase the average luminosity is to reduce β^*. However in reducing β^* also the beam lifetime will decrease due to the larger rate of nuclear reactions. To keep a net benefit in terms of integrated luminosity one should reduce the ratio of the turnaround time over the luminosity lifetime and hence decrease as much as possible the elapsed time between two consecutive runs [8].

The emerging scenarios for the LHC performance upgrade are the short-bunch and the long bunch schemes, listed in Table 1. The former is the today's baseline choice, although handling the enhanced beam power and the e-cloud is cumbersome and has yet to be assessed. A so-called superbunch scheme, with a single very long dense bunch per beam and a considerably smaller circulating current has also been investigated and finally abandoned since the total number of events per crossing of 5×10^5 is incompatible with the state of the art of particle detector technology.

New insertions

Many IR layout variants are under scrutiny to reduce β^* [8]. Alternatives are considered, such as dipole first versus quadrupole first, round versus elliptic beam shape at the IP, high-field versus low-field triplets and trade-off between β^* and l^*, the free-space around the IP. When reducing β^*, the beam size in the triplet and the crossing angle will be larger. This introduces the need of increasing at the same time the focussing strength and the aperture in triplets. The present generation of IR quadrupoles has exploited almost the full potential of Nb-Ti conductor and can hardly provide better performance. A new generation of quadrupoles is required, making use of more efficient SC materials, such as Nb_3Sn. Although Nb_3Sn is well known for more than four decades, its practical use for accelerator magnets is yet under study. Outstanding technological issues, mostly related to the ability of building Nb_3Sn long coils, and full-length magnet prototypes, are still open and require aggressive R & D plans to be solved. The use of separating dipoles as the first magnetic element close to the IP has some positive aspects. The number of parasitic beam-beam interactions is considerably reduced. The triplet can be made with two-in-one quadrupoles, avoiding off-axis beam traversal, which in turns requires less mechanical aperture. The collision debris will cross the dipole first, which will act as an efficient spectrometer protecting the triplet. There are however some basic drawbacks. The dipole should be protected from radiation damages, which is most likely not easier than protecting the quadrupole. The distance of the triplet from the IP will unavoidably increase, with a consequent increase of the peak-β and of the chromatic aberrations. This will limit the mechanical aperture in the triplets and affect the stability of the single particle motion due to the increase of the chromaticity correction. Also in this case there is a strong incentive to develop Nb_3Sn cables with the aim of building the shortest possible high-field separation dipoles, thereby reducing the distance of the triplet from the IP, the peak-β and chromaticity.

Beams with elliptical shape at the IP require a smaller crossing angle when they interact in the plane where the beam size is larger. A flat beam shape can be obtained either by powering the present triplet as a doublet [9] or by changing the triplet gradients [10]. Assuming that $\varepsilon_x = \varepsilon_y = \varepsilon$, $\beta_x^* \equiv r\beta^*$ and $\beta_y^* \equiv \beta^*/r$, for $r > 1$, the reduction of the crossing angle and the luminosity gain are respectively:

$$\frac{\theta_{c,E}}{\theta_{c,R}} = \sqrt{\frac{\beta_R^*}{\beta_E^*}} = \frac{1}{\sqrt{r}}, \quad \frac{L_E}{L_R} = \frac{1}{\sqrt{1+\left(\theta_{c,R}\sigma_z/2r\sigma^*\right)^2}},$$

where R and E indicate respectively round or elliptic shape. The potential luminosity gain may reach 50 %, provided one can stand the parasitic beam encounters.

Reducing the Piwinki ratio, hence increasing the geometric factor F, results in a further luminosity increase. Various scenarios are under investigations. One can reduce the bunch length σ_z adding more RF power. The modification is rather expensive but very effective. One can also reduce θ_c by adding crab-cavities around the IP. The advantage is that much less RF power is required but the control of the RF phase and the noise rejection will become very serious issues, whilst additional cavities must be inserted in each IR. Separation dipoles very close to the IP are another economic way to reduce θ_c at the IP whilst keeping it almost nominal afterwards. Preliminary investigations have shown that the new separation scheme with a reduced distance at the parasitic encounters has tolerable effects on beam dynamics. However the integration of the dipoles may imply deep modifications of the experimental apparatus [11].

LHC INJECTION ENERGY

Injecting 1 TeV beams in the LHC is an old idea, which should guarantee a larger normalized aperture and more stable, more linear magnetic fields. This should also allow accumulating larger circulating current and shorten the turnaround time.

Injecting at higher energy is also a necessary step to eventually push the LHC beam energy beyond the ultimate value of 7.7 TeV per beam, while keeping the same momentum swing during the ramp.

Reduction of the turnaround time

Dynamic effects due to persistent currents are known to give difficulties at injection in all SC colliders and are expected to complicate the setting-up of the LHC. Doubling the injection energy would double the normalized acceptance of the LHC and at the same time make the magnetic cycle 2.6 times more stable at the flat bottom and during the snap-back, as shown by recent measurements. This would result in a significant simplification of the setting-up and possibly help in reducing from 10 to 5 hours the elapsed time between two consecutive runs. The expected gain is shown in Table 3, assuming that the luminosity decays exponentially and that the optimal run time T_{run} and the integrated luminosity fulfil:

$$1+\frac{T_{run}+T_{turnaround}}{\tau_L}=e^{\frac{T_{run}}{\tau_L}},$$

$$\int_0^{T_{run}} L dt \approx \frac{L_0\tau_L}{T_{run}+T_{turnaround}+\tau_L}.$$

Increase of the beam current

Injecting more current with constant brightness, within the same LHC physical aperture will increase the peak luminosity, which, at the beam-beam limit, is proportional to the normalized emittance $\varepsilon_n = \beta\gamma\varepsilon$, as shown in the approximate formula below:

$$L \approx \gamma \Delta Q_{bb}^2 \frac{\pi \varepsilon_n f_{rep}}{r_p^2 \beta^*}\sqrt{1+\left(\frac{\theta_c\sigma_s}{2\sigma^*}\right)^2},$$

where ΔQ_{bb} is the linear tune shift, f_{rep} is the collision repetition rate, r_p is the classical radius of the proton, σ^* is the rms transverse beam size, and σ_s, θ_c, β^* have the same meaning as in Table 1.

Injecting at 1 TeV will double the normalized acceptance and impose a factor √2 larger crossing angle to keep constant the relative beam separation at the parasitic crossing, according to:

$$\frac{d}{\sigma} \approx \theta_c\sqrt{\frac{\gamma\beta^*}{\varepsilon_n}}.$$

This will result in a less than twofold increase in luminosity due to reduction of the geometric factor F. The hope is to introduce some effective compensation scheme of far beam-beam interactions to avoid increasing the crossing angle and to obtain the full luminosity gain [12].

Table3: integrated luminosity versus turnaround time

L [cm^{-2}s^{-1}]	τ_L [h]	$T_{turnaround}$ [h]	T_{run} [h]	$\int_{200\text{ runs}} L\,dt$ [fb^{-1}] gain	
10^{34}	15	10	14.6	66	×1.0
10^{34}	15	5	10.8	85	×1.3
10^{35}	6.1	10	8.5	434	×6.6
10^{35}	6.1	5	6.5	608	×9.2

AC-type SC magnet development

The present knowledge on AC-type SC magnets can be summarized by iron dominated magnets with internally cooled cables, based on the JINR Nuclotron design [13], and by the GSI001 model [14], based on a modified RHIC type dipole, built by LBNL in the R&D framework for the FAIR Project at GSI.

Fast magnets for possible LHC injector upgrades imply a considerable improvement in the state of the art, in particular in reducing the magnet losses during the field ramps and in increasing the efficiency of heat removal away from the cable. The development of low losses SC cables for dipoles achieving peak fields in the range of 3÷5 T and ramps of 1÷5 T/s is to be planned. This appears feasible in about half a decade. Should the beam losses be seen as a critical issue in specific accelerator areas, the use of magnets with internally cooled SC cables can be considered.

AC-type SC magnets are considered for high-field variants of the PS and of the SPS successors, eventually to inject 1 TeV beams in LHC.

INCREASE OF THE BEAM ENERGY

The LHC collision energy may slowly ramp up to the ultimate value of 7.7 TeV corresponding to a peak field of 9 T in the dipoles. Further energy increase will require replacing the main magnets. With Nb_3Sn one should reach 15 T in the dipoles and 320 Tm^{-1} in the quadrupoles, within the present apertures.

High-field SC magnet development

Important progress was achieved in recent years in the manufacture and use of Nb_3Sn wires, specifically thanks to the ITER model coils with about 30 t of Nb3Sn wires manufactured and the US National Program for high-current density Nb_3Sn wires and dipole models opening the 10-to-15 T field range. However a considerable step forward is still needed in the next decade to optimize the wire for application in accelerator magnets, to set up magnet designs and fabrication techniques providing the required performance and magnetic field quality, and finally to substantially decrease manufacture costs of both wires and magnets for a large application as in the LHC.

CONCLUDING REMARKS

The optimal performance upgrade for LHC is still under study. Even if the basic steps and the critical issues are well identified, additional information has to be gathered in the early operation period, especially in the machine protection, collimation and e-cloud dynamics.

The consolidation of the existing infrastructure and the completion of the LHC to the nominal design are high-priority tasks. A luminosity gain of a factor two is expected from the reduction of β^*. The appealing way to go is to replace the existing triplets with higher gradient larger aperture quadrupoles, based on Nb_3Sn cables. This implies launching the development of such magnets. However, to prevent the risk of delayed results it is wise pursuing alternative studies of IR layouts based on Nb-Ti SC. Compensating the effect of the crossing angle at the IP is another crucial issue. The crab-cavity and the early separation scheme have a good potential of luminosity gain, however, they are both not yet ready. Far beam-beam compensation is the workhorse solution to be pursued. The safer way to go is to reduce the bunch length, hence to increase *F*, introducing additional cavities. Doubling the number of bunches, thereby reducing the number of event per crossing is another very appealing proposal. In strong favour of it is a collision regime more appropriate for the number of events per crossing, whilst counter-indications come from e-cloud simulations and from the forecasted thermal load. Increasing the intensity will imply dealing with a larger beam power. Doubling the LHC injection energy will ease the operation and give the potential for an additional luminosity gain; at the same time it is the right move towards the increase of the collision energy in LHC.

As shown in Table 4 the potential gain in luminosity is very large. This should provide with a comfortable margin an integrated luminosity at least an order of magnitude over the nominal figure. However to fully exploit the new mode of operation a considerable effort is required in improving the experimental detectors.

Increasing LHC collision energy is a more complex programme, requiring major R&D effort and industrial investments to produce more performing magnets and to improve many other accelerator components.

Table3: Factorization of the expected luminosity gain with respect to the nominal value.

gain	applied method
×2	ultimate performance with I=0.86 A
×2	new IR design with $\beta^* = 0.25$ m
×2	short bunches with Δt_{sep}= 12.5 ns (or long bunches with N_b= 6 10^{11})
×1.4	halve the turnaround time to 5 h
×2	inject at 1 TeV and double the N_b and ε_n

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