UPGRADE ISSUES FOR THE CERN ACCELERATOR COMPLEX[#]

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Abstract

The Large Hadron Collider (LHC) at CERN is at a very advanced stage of hardware commissioning and the first beam collisions in the experiments are expected during the year 2008. In line with the recommendations issued in 2006 by the European Strategy Group for Particle Physics, work has now started for maximizing the physics reach of the LHC and for preparing for other foreseeable needs. Beyond upgrades in the LHC itself, mainly in the optics of the insertions, the injector complex has to be renewed to deliver beam with upgraded characteristics with a high reliability. In a first phase, a new 160 MeV H^- linac ("Linac4") will be built to replace the present 50 MeV proton linac (Linac2) and extensive consolidation will be made. In a second phase, the present 26 GeV PS and its set of injectors (Linac2 + PSB) are planned to be replaced with a ~50 GeV synchrotron ("PS2") using a ~4 GeV superconducting proton linac ("SPL") as injector. The SPS itself will also be the subject of major improvements, to be able to cope with a 50 GeV injection energy and with beams of much higher brightness. These proposals are described as well as their potential to evolve and fit the needs of future facilities for radioactive ions and/or neutrinos.

INTRODUCTION

The LHC has been designed for colliding proton bunches spaced by 25 ns at a centre of mass energy of 14 TeV with a nominal luminosity of 10^{34} cm^{-2}s^{-1} in two interaction regions [1]. The luminosity of 2.3×10^{34} cm^{-2}s^{-1} has often been quoted as the ultimate that could be reached without major upgrades (see Table 1). After 8 to 10 years, depending upon the rate of ramp-up of the LHC performance, the halving time of the statistical experimental errors will exceed 5 years. It is therefore reasonable to plan for a major upgrade of the LHC and the injector complex around the year 2017, aiming at much higher luminosities to increase the physics reach (a factor of 10 would increase the discovery range for new particles by about 25 % in mass [2]). Started at CERN in 2001 [3] and summarised by the PAF working group [4], the analysis of possible scenarios for increasing the LHC characteristics has benefited of the work done in the context of the CARE-HHH network with the support of the European Union [5] in collaboration with US-LARP supported by the DOE [6].

LHC UPGRADE

First priority improvements

The LHC will benefit from the existing complex of injectors which can already provide the beam necessary for reaching the nominal luminosity of 10^{34} cm^{-2}s^{-1}. As initially built, however, it will not be able to exceed that level because of hardware limitations in collimators and IR magnets. The "Collimation – Phase 2" development [7] has therefore been launched to design a solution allowing for a circulating beam current beyond the "ultimate", while the initial collimation system will limit it to ~40% of nominal. Similarly, a first project of "IR upgrade" has also begun, with the goal of providing in 2012 larger aperture NbTi triplet magnets using existing spare dipole cable and capable to achieve a β* of 0.25 m and a maximum luminosity of 3×10^{34} cm^{-2}s^{-1} [8]. To exploit the full potential of these improvements, the injector complex will also have to benefit from a first upgrade described later in this paper to be able to deliver the "ultimate" type of beam.

Luminosity parameters

The maximum tolerable head-on beam-beam tune shift of ~0.01 sets a fundamental limit to the operation of the collider. In the case of the LHC with round beams filling similarly both rings with alternating planes crossing at two interaction points, the total beam-beam tune shift can be written as [9]:

$$\Delta Q_{bb} \cong -\frac{N_b}{\varepsilon_N}\frac{r_p}{2\pi\sqrt{1+\phi^2}}\,, \qquad (1)$$

where N_b is the number of protons per bunch, ε_N the normalized rms transverse emittance and ϕ the "Piwinski angle" defined as:

$$\phi = \theta\sigma_Z/(2\sigma^*)\,, \qquad (2)$$

σ^* being the rms transverse beam size at the interaction point, σ_z the rms bunch length and θ the crossing angle.
The luminosity can be expressed as:

$$L \cong \frac{f_{rev}\gamma}{2r_p} n_b \frac{1}{\beta^*} N_b \Delta Q_{bb} F_p F_{hg}\,, \qquad (3)$$

where f_{rev} is the revolution frequency, n_b the number of bunches, β* the beta function at the interaction point, F_p a form factor resulting from the longitudinal bunch profile (1 for a Gaussian and $\sqrt{2}$ for a uniform profile) and F_{hg} the factor resulting from the "hourglass" effect (<1 when bunch length > β*).
The beam brightness N_b/ε_N is an essential characteristic of the beam that results directly from the values of ϕ and ΔQ_{bb} through equation (1). The classical option is to minimize it as well as N_b and hence to look for the minimum value of ϕ compatible with a crossing angle providing enough separation between beams (reduction of the long range beam-beam effects). For example in the cases of the nominal luminosity ϕ=0.4, and it is 0.75 for the ultimate. Once the emittance ε_N is fixed, N_b is also

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fixed because brightness is imposed, so that the only possibilities left for increasing the luminosity (see Eq. 3) are to reduce β^* and/or to increase n_b. Although favoured for the detectors because of the smaller number of events per bunch crossing, the scenarios based on a number of bunches higher than nominal (or with time intervals between bunches smaller than 25 ns) have been abandoned, mainly because of heat load on the beam screen and of e-cloud effects [10]. β^* is therefore the only parameter left for optimizing luminosity. It is the main ingredient for 2 schemes envisaged for the LHC luminosity upgrade [11], "Early Separation" (ES) and "Full Crab Crossing" which both aim at the challenging value of β^*=8 cm with a Piwinski angle equal to 0 (see Table 1). In the ES scheme (Fig. 1) the 2 beams collide with a small angle and the separation to reduce the long range beam-beam effect is obtained with "D0" dipoles installed close to the interaction point. In the FCC scenario, the trajectories of the beams make a 673 µrad angle, but the bunches are tilted by transverse deflecting fields in Crab cavities and they cross as if aligned (Fig. 2). A less conventional solution is to use a Large Piwinski Angle (LPA) and long bunches with a uniform longitudinal distribution. Very long bunches have however been discarded because they are impractical for the detector electronics. An interesting LPA scenario assumes ϕ~2 and hence a larger value of N_b / ε_N (Eq. 1), coupled with a less demanding β^* of 25 cm. For the same ε_N and ΔQ_{bb} as in the other schemes, the luminosity is increased in proportion to N_b (Eq. 3). To limit the total circulating current and reduce the heat load on the beam screen, the number of bunches is divided by two (time interval between bunches: 50 ns). Moreover, wire compensation is planned to compensate for the long range beam-beam effect (Fig. 3).

Comparison of luminosity upgrade options

A crucial parameter for the experiments is the average luminosity L_{av}, which depends upon the turnaround time T_{ta} (time interval between two successive data taking periods), the peak luminosity $\hat{L}$ and the luminosity lifetime τ_L. The time dependence of luminosity is different for the ES/FCC and LPA upgrade scenarios, as visible in Figure 4, drawn with the typical assumption that T_{ta} =5h. All scenarios can provide a similar L_{av}, but the initial luminosity is much larger for ES and FCC and it decays much faster. Because of the smaller number of bunches, the number of events per bunch crossing is however always larger in the LPA scenario.

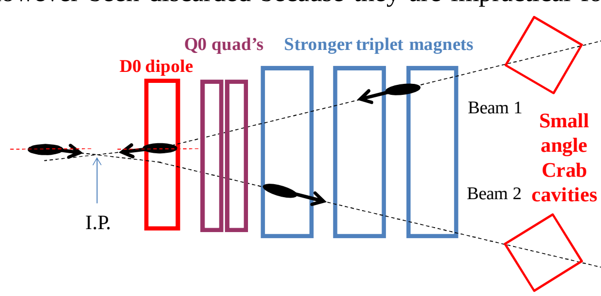

Figure 1: Interaction region for the Early Separation (ES) scheme with very small β^* (8 cm) and early separation dipoles D0 close to the interaction region.

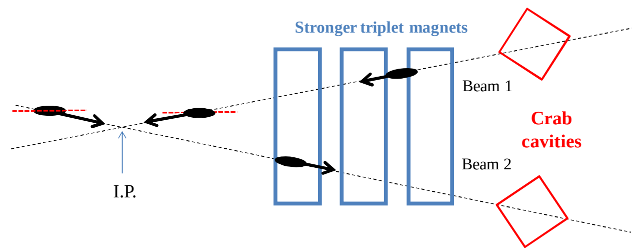

Figure 2: Interaction region for the Full Crab Crossing (FCC) scheme with very small β^* (8 cm) and crab cavities for tilting the bunches.

Table 1: Scenarios for optimizing the luminosity in LHC (ε_N=3.75 µrad in all cases).

	Symbol	Nominal	Ultimate	ES or FCC	LPA
Number of bunches	n_b	2808	2808	2808	1404
Bunch spacing	Δt_{sep} [ns]	25	25	25	50
Protons/bunch	N_b [$\times 10^{11}$]	1.15	1.7	1.7	4.9
Average beam current	I [A]	0.56	0.86	0.86	1.22
rms bunch length	σ_z [cm]	7.55	7.55	7.55	11.8
Longitudinal factor (profile)	F_p	1 (Gaussian)	1 (Gaussian)	1 (Gaussian)	$\sqrt{2}$ (Uniform)
Beta function at IP 1 and 5	β^* [m]	0.55	0.5	0.08	0.25
Crossing angle	θ [µrad]	285	315	0 or 673	381
Piwinski angle	ϕ	0.4	0.75	0	2.01
Hourglass factor	F_{hg}	1	1	0.86	0.99
Peak luminosity	$\hat{L}$ [$\times 10^{34}$ cm^{-2}s^{-1}]	1	2.3	15.5	10.6
Initial luminosity lifetime	τ_L [h]	22	15	2.2	4.5
Average luminosity (T_{ta}=5h)	L_{av} [$\times 10^{34}$ cm^{-2}s^{-1}]	0.6	1.2	3.6	3.5

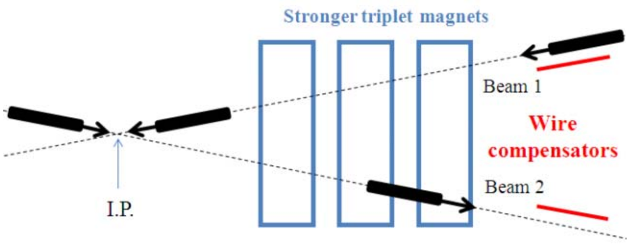

Figure 3: Interaction region for the Large Piwinski Angle (LPA) scheme with moderate β* (25 cm) and wire compensators against long range beam-beam effects.

Although never implemented in practice in any hadron collider (background in the experiment and risk of triplet quenches), luminosity levelling would be very valuable. It could be achieved by acting upon β* in all cases and eventually also on bunch length in the LPA case or crossing angle for ES [11].

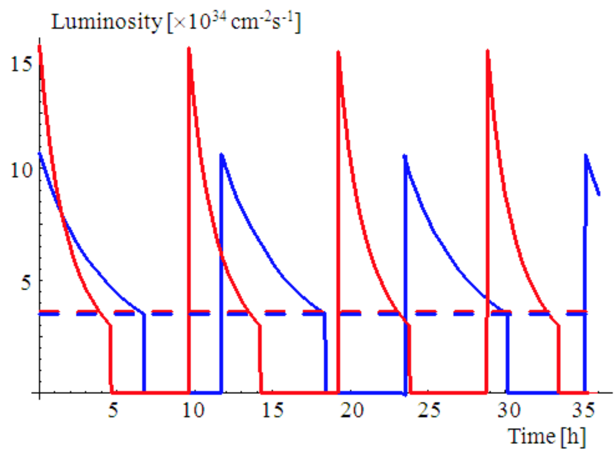

Figure 4: Time dependence of luminosity for the ES or FCC (red) and LPA (blue) schemes assuming a turnaround time of 5h. The average luminosities are represented by the dashed lines.

INJECTORS' UPGRADE

Motivation

The different scenarios foreseen for increasing the luminosity of the LHC require improved beam characteristics from the injectors, out of reach of the present complex [12]. Hence is it necessary to plan for new accelerators that can satisfy the needs of the most demanding scenario with a reasonable operational margin.

Moreover, the generation of the beam for LHC is using sophisticated beam gymnastics and pushing the equipment in the injectors to its limit, which combines with the age of many components to degrade reliability. That will be especially unacceptable for the upgraded LHC whose integrated luminosity will strongly depend upon the dead time between physics coasts (T_{ta}).

Main design choices

The present complex of accelerators deals with multiple types of particles and supplies beam to numerous experiments (Fig. 5). Any proposed upgrade has to take into account the future of the existing facilities as well as the possibility to accommodate new ones. In the case of the proton beam for LHC, the cascade made up of Linac2 (50 MeV proton linac), PS Booster (1.4 GeV, 4 rings slow cycling synchrotron), PS (26 GeV) and SPS (450 GeV) is being used.

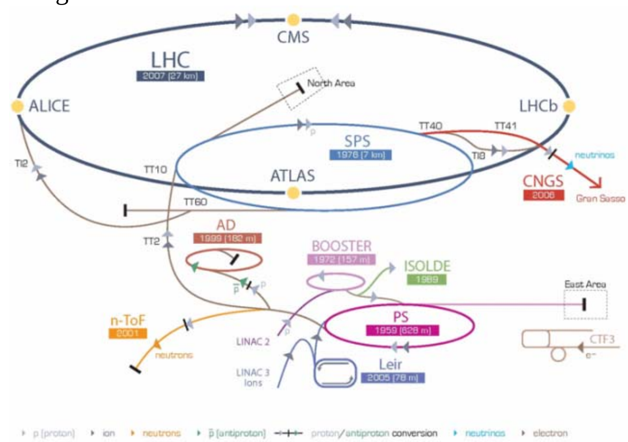

Figure 5: CERN accelerator complex.

The analysis of the working group on Physics Opportunities with Future Proton Accelerators [13] has been used as an input for preparing proposals concerning the accelerators. The beam brightness goal has been set at twice the ultimate intensity per bunch within the nominal emittances at 7 TeV in the LHC, assuming realistic transfer efficiencies through the SPS and LHC. It dictates the choice of the injection energy in space charge dominated synchrotrons because of its contribution to the incoherent space charge tune spread:

$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \frac{R}{\beta\gamma^2} \qquad (4)$$

where N_b is the number of protons per bunch, $\varepsilon_{X,Y}$ the normalized transverse emittances, R the mean radius of the accelerator, and β and γ are classical relativistic parameters. This is taken care of in the proposed future accelerator complex shown in Figure 6 together with the present machines. The layout of the new accelerators on the CERN site is shown in Figure 7.

Future accelerator complex

The SPS is the only accelerator which is not replaced, but its injection energy is brought up to 50 GeV to reduce space charge effects (Eq. 4) and to be far away from transition (~23 GeV). Additional important upgrades will also be necessary to reduce electron clouds and their effects, to decrease impedance and to consolidate and possibly improve the RF systems.

A new synchrotron (PS2, compared to the present PS in Table 2) will accelerate protons up to 50 GeV. To be able to fill the SPS with a single pulse using 5 turns "islands ejection" [14], its circumference has to be slightly smaller than 1/5 of the SPS. For the needs of cogging with bunches spaced by 25, 50 or 75 ns, the length of PS2 will be precisely 15/77 of the SPS. Because of space charge (Eq. 4), the injection energy of protons in PS2 has to be at least 4 GeV. For fixed target physics with the SPS, PS2 will also supply a beam bunched at 40 MHz, although within larger transverse emittances. The heavy ion beam for LHC will be sent from LEIR to PS2 through the TT2-TT10 transfer tunnel. Acceleration and beam gymnastics in PS2 will require the RF system to operate over the frequency range 18-40 MHz.

Table 2: PS2 characteristics (with respect to the PS).

	PS2	**PS**
Injection energy (kinetic) [GeV]	4	1.4
Maximum energy (kinetic) [GeV]	50	25
Cycle time [s]	2.4	2.4
Nb max for LHC (25ns spacing)	4×10^{11}	1.7×10^{11}
Nb max for fixed target physics	1.2×10^{14}	3.3×10^{13}
Maximum energy per pulse [kJ]	1000	70
Maximum beam power [kW]	400	60
Circumference [m]	1346	628

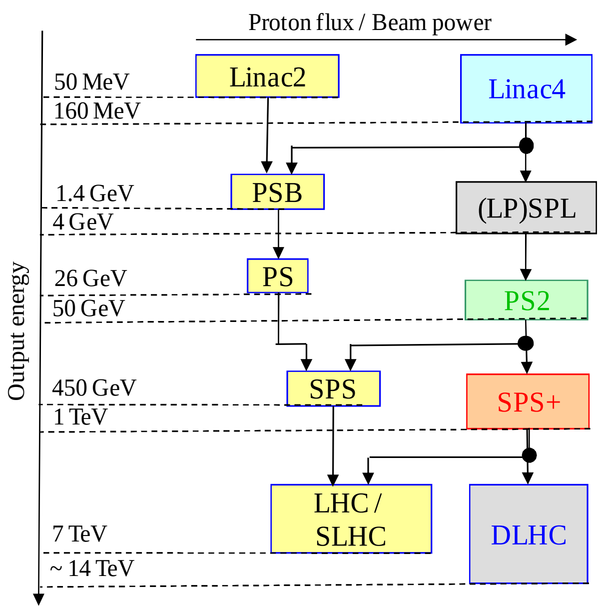

Figure 6: Present and proposed future accelerators:
- Linac4: 160 MeV H- linac
- (LP)SPL: (Low Power) Superconducting Proton (H-) Linac (~5 GeV)
- PS2: new proton synchrotron (~50 GeV)
- SPS+: superconducting SPS (~1 TeV)
- SLHC: LHC with luminosity upgrade
- DLHC: double energy LHC.

The proton beam will be accumulated in PS2 by charge exchange injection of H- ions from a Superconducting Proton (in fact H-) Linac (SPL) [15]. For the needs of LHC and SPS, a Low Power version of the SPL (LPSPL) will be built, capable of delivering 20 mA beam current at a 2Hz repetition rate. It could later be upgraded to a multi-MW beam power and to an energy of 5 GeV at a fraction of the cost of a dedicated accelerator (Table 3).

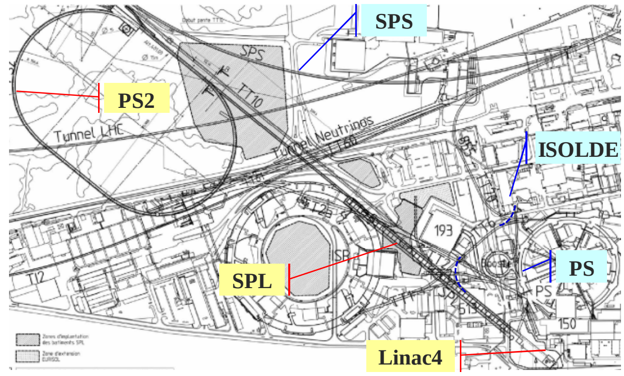

Figure 7: Layout of the new injector complex.

Table 3: LPSPL and SPL characteristics.

	LPSPL	SPL
Beam energy (kinetic) [GeV]	4	5
Cycle time [ms]	500	20
Beam pulse duration [ms]	1.2	0.4
Average current during pulse [mA]	20	40
Nb max for fixed target physics	1.4×10^{14}	1×10^{14}
Beam power [MW]	0.19	4
Length [m]	460	535

Implementation phase 2008-2012

The low energy front end of the SPL (up to 180 MeV) will be using normal conducting accelerating structures. The part up to 160 MeV is called Linac4 [16]. Its construction has started in January 2008 in view of replacing the present Linac2 as injector of the PSB in 2013, boosting performance for LHC by dividing by two the space charge effect at injection in the PSB, reducing the filling time of the LHC and increasing the reliability. Linac4 will be installed in a new building located where the low energy front end of the SPL has to be. It is the main improvement of the injector complex that will enable it to provide the ultimate beam characteristics to the LHC, hence allowing to draw the full benefit from the improvements made in the mean-time to the LHC itself (see before).

During the period 2008-2011, the design of the LPSPL, of PS2 and of the necessary SPS improvements will be studied [17, 18, 19] and critical hardware components will be developed (superconducting cavities and cryomodule for the LPSPL, tuneable RF cavity for PS2, surface treatment of the SPS vacuum chamber to reduce secondary electron yield...) in view of submitting Technical Design Reports and cost estimates by mid-2011. During the same period the different possible options to increase by a significant factor the integrated luminosities (ES, FCC, LPA...) have to be analysed and compared in detail. Hardware prototypes should be developed and machine experiments made to demonstrate the feasibility of the selected scheme.

Implementation phase 2012-2017

If the construction of the new injectors starts at the beginning at 2012, beam commissioning without interference with physics could take place in 2016. The improvement of the SPS (vacuum chamber and impedance reduction) should preferably be done simultaneously. The SPS will have to be modified for connection with PS2 and injection at 50 GeV during a ~6 months shutdown in 2016-2017. After a short beam commissioning period, the upgraded beam will be available to the LHC in the course of 2017. The upgrades of the LHC IRs and of the experiments could either be implemented during the same shutdown or at a later stage. Once they are installed, probably in 2017 or 2018, the event rate in the experiments should reach new record levels, up to 10 times higher than with the nominal LHC performance.

Other possible upgrades

The potential to increase the SPS proton flux with the new injectors could be used for a conventional neutrino superbeam [20].

The LPSPL could be upgraded to a multi-MW beam power, doubling the number of klystrons to raise the beam current to 40 mA and upgrading the infrastructure (water, cryogenics electricity and power supplies) to increase the repetition rate to 50 Hz. Such a proton driver would meet the needs of a Radioactive Ion Beam facility of the next generation (EURISOL [21]) at a fraction of the cost of a dedicated accelerator. With a slight extension in energy (+1 GeV) and the addition of an accumulator and a storage ring, it could become the proton driver of a neutrino facility [22]. The location foreseen for the LPSPL (Figure 7) is compatible with both new experimental facilities.

In the longer term, the SPS could be replaced by the SPS+, a new synchrotron equipped with superconducting magnets to reach an energy of approximately 1 TeV. Once the physics potential of the LHC will have been exhausted, the option to rebuild it with much higher field dipoles (>18 T) will be worth considering. The SPS+ would then be an ideal injector for such a “Double energy LHC” (DLHC).

CONCLUSION

Conforming to the statements of the European Strategy Group for Particle Physics [23], the accelerator upgrades described in this paper are meant to provide the capability to maximise the physics reach of the LHC while maintaining a physics programme as broad as possible and preparing for potential future extensions. Linac4 will replace Linac2 in 2013. Design reports and cost estimates for all the other accelerators are being prepared for mid-2011. The first physics results of the LHC will be crucial elements for a decision of construction at the beginning of 2012. In the best case, the SLHC and its new injectors could start operating in 2017.

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