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Preliminary accelerator plans for maximizing the integrated LHC luminosity

M. Benedikt, R. Garoby, F. Ruggiero, R. Ostojic, W. Scandale, E. Shaposhnikova, J. Wenninger

1. Introduction

A working group on "Proton Accelerators for the Future" (PAF) has been created in May 2005 by the CERN direction to elaborate a baseline scenario of the possible development and upgrade of the present Proton Accelerator Complex [1]. This report is the result of the investigation conducted until the end of 2005, in close connection with the working group on "Physics Opportunities with Future Proton Accelerators" (POFPA) [2] and is consistent with their recommendations [3].
Focused on the goal of maximizing the integrated luminosity for the LHC experiments, a scenario of evolution is proposed, subject to further refinement using the future experience of commissioning and running-in the collider and its injector complex. The actions to be taken in terms of consolidation, R & D and improvement are outlined. The benefits for other types of physics are mentioned and will be investigated in more detail in the future.

2. Status of the LHC injectors

The existing complex of proton accelerators (Linac2, PSB, PS and SPS) has been instrumental to the decision of building the LHC [4] and will be crucial for its regular operation. However, these machines have been built a long time ago for different purposes and they have suffered from reduced preventive maintenance during the recent years.

2.1 Needs for consolidation

Of particular concern are the PS and SPS main magnets, which are showing worrying signs of aging due to the combined effects of mechanical fatigue, corrosion and irradiation.

Moreover, the beam loss due to the increased number of protons that have to be accelerated in the period 2006-2011 will create damages and complicate/lengthen interventions and repairs on the accelerator equipment.

PS

Triggered by alarming observations in 2003 and 2004, Phase 1 of an extensive consolidation project of the PS dipoles has been launched, and the 25 most critical magnets have been refurbished during the shut-down in 2005. Because of the limited number of spare magnets and of the absence of scheduled long shutdown in the future, this first phase, which covers a total of 50 devices, will last until 2010. The refurbishment of the remaining 50 magnets (consolidation Phase 2) is proposed as a cost effective way to minimize the risks of disturbing LHC operation and keep the PS operational well beyond 2015. Until the end of this consolidation, the mean cycling rate and the thermal load should not be increased.

SPS

The SPS magnets also show worrying signs of aging. Water leaks have shown up in 2004, resulting in a downtime of about one day per event (for a total of 7 in 2004). As of today, non-destructive inspection techniques of the magnet cooling circuits are not available. More efforts will be devoted to this subject in 2006, with the goal of proposing an adequate consolidation programme before the end of the year. In these conditions, the thermal load should not be increased and the high energy flat tops should not be lengthened, as discussed for fixed target physics.

2.2 Performance limitations

Two levels of performance have been defined for the LHC, which correspond to two different sets of beam characteristics called “nominal” and “ultimate” (see Appendix). The foreseen scheme of operation of the injectors (Vol. 3 in ref. [4]), based on Linac2, PSB, PS and SPS, has proven to be able to deliver the nominal beam at 450 GeV, but falls short of reaching the ultimate beam.

PSB

Injection in the PSB is a well identified bottle-neck for the generation of the type of high brightness beams required for LHC, because of space charge effects at 50 MeV.

The favored solution to increase the brightness up to the ultimate level and help cover the needs of the future LHC luminosity upgrades is to build a new Linac (Linac4) delivering H^- at 160 MeV, thus halving space charge at injection in the PSB (Session 5 in ref. [5]). It will also result in a reduction of the LHC filling time and an increased reliability.

PS

Space charge at low energy in the PS is not expected to be a limitation up to the ultimate brightness. Moreover, once Linac4 is available, the situation will be further eased because the beam will be delivered in a single shot by the PSB and accelerated immediately after injection.

SPS

So far, the nominal LHC intensity is the maximum obtained at 450 GeV in the SPS. Predictions for ultimate LHC intensity are based on scaling and need experimental confirmation. The main difficulty in achieving the required transverse emittances is the vertical single bunch instability due to electron cloud. The transverse mode-coupling instability could also create serious problems for higher LHC intensities. In addition to the extraction kickers which have already been identified as a troublesome source of transverse impedance, other sources are likely to exist. Preliminary studies show that significant improvements for these problems can be expected from a higher SPS injection energy (40-60 GeV).

3. LHC luminosity upgrade [5, 6]

The LHC luminosity will gradually increase until the nominal bunch population is exceeded and the injectors reach their limits in terms of brightness. The LHC luminosity upgrade will comprise several phases. All scenarios examined today include an increase of beam current and modifications of the two high luminosity insertion regions (ATLAS & CMS).

The initial phase concerns the increase of the beam current to the ultimate value. Operating regularly at this intensity will require improvements from the injectors, as described in the previous section. It will eventually lead to a peak luminosity of 2.3×10^{34} cm^{-2} s^{-1}.

The baseline luminosity upgrade scenario relies on new Interaction Regions to reduce β^* from 0.5 to 0.25 m and increase the crossing angle by a factor $\sqrt{2}$, to keep the same relative beam separation at the parasitic collision points. The corresponding peak luminosity is multiplied by a factor 2, provided the bunch length is halved by means of a new RF system. This scheme is the safest option in terms of beam dynamics, machine protection, and radiation risks, but the new IR magnets are challenging.

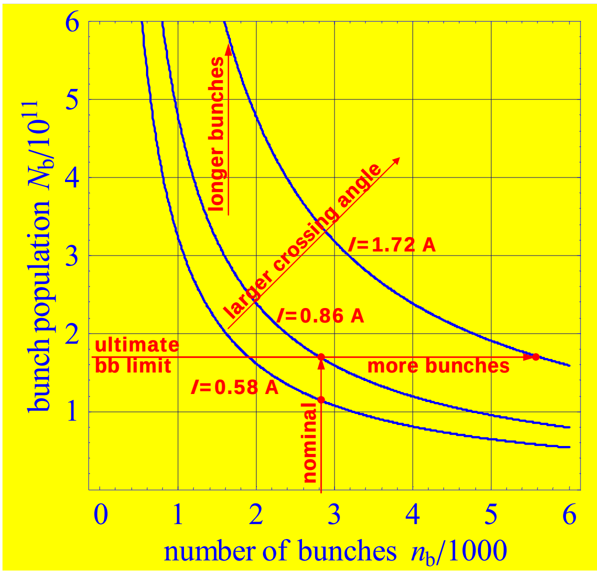

Figure 1: Possible scenarios for LHC luminosity upgrade

Further increases in luminosity involve major modifications of several LHC sub-systems and of the injector chain to exceed the ultimate beam intensity and possibly to inject into the LHC around 1 TeV. The possible scenarios are illustrated in figure 1. The LHC peak luminosity at the beam-beam limit depends on the ratio I/β^*, where the total beam intensity I is limited by the injectors and by electron cloud effects, collimation and machine protection in the LHC. The minimum crossing angle depends on the beam intensity and is limited by the triplet aperture. If the injectors are upgraded to provide a higher brightness N_b/ε_n, longer bunches will allow increasing luminosity without exceeding the beam-beam limit. We also anticipate less electron cloud and RF heating effects for longer bunches: a luminosity gain of about 50% is possible for flat bunches longer than β^*. However the event pile-up in the physics detectors increases with the bunch population N_b and colliding more bunches with a shorter bunch spacing is therefore the preferred option for the experiments. Finally, the luminosity lifetime at the beam-beam limit depends only on β^* and a key factor to increase the integrated luminosity is a substantial reduction of the machine turn-around time.

To increase the luminosity beyond the possibility of the baseline scenario requires an increased number of bunches and may not be compatible with electron cloud and long range beam-beam effects. Different bunch distances are being considered; 12.5 ns is presently favored by the experiments and would yield a peak luminosity of $9.2\cdot10^{34}$ cm^{-2} s^{-1}, while a multiple of 5 ns is preferable for the accelerators.

Dynamic effects due to persistent currents are known to give difficulties at injection energy in all superconducting colliders and are expected to complicate the setting-up of the LHC. Doubling the injection energy would make the magnetic cycle more stable and double the normalized acceptance of the LHC. This would result in a significant simplification and shortening of the setting-up, with a direct benefit for the turn-around time and the integrated luminosity. Luminosity could then possibly be increased by injecting bunches of nominal brightness but larger transverse emittances. Finally, it would also be a natural first step towards a future LHC energy upgrade.

4. Proposal

Based on the above-mentioned analysis, the accelerators in the injector complex are proposed to be ultimately replaced, as sketched in figure 2, and the LHC itself has to be progressively upgraded. The following scenario is therefore envisaged.

4.1 Consolidation of injectors

Consolidation is essential to guarantee a reliable operation of the injector complex and hence to minimize turn-around time and maximize the integrated luminosity. Dipole magnets in the PS and SPS are clearly identified as likely sources of faults which have to be consolidated. More generally, enough resources must be dedicated to consolidation of aging equipments to reduce the risk of detrimental effects on LHC operation.

4.2 LHC completion

In the LHC itself, the focus will first be on progressively reaching the nominal characteristics and preparing for the ultimate performance. This implies to upgrade the initial hardware used e.g. for collimation, dump and RF, to make it able to handle the nominal and possibly ultimate beam current.

4.3 Improvements

Filling the LHC should be made as fast as possible. The basic period can be reduced, resulting in shorter cycles of the PSB and PS. Moreover the SPS acceleration time can also be shortened. This has to be implemented in the short term, keeping the average thermal load constant for the PS and SPS magnets until they are felt dependable enough.

All possible means to reduce beam loss should be pursued. The proposed project for a new multi-turn ejection from the PS is particularly relevant and deserves a high priority, because it is expected to reduce loss at 14 GeV/c by a factor of ~3 for the high intensity/high flux beam for the CERN Neutrino to Gran-Sasso experiment.

Improvements must be implemented to prepare the injectors for delivering the ultimate type of beam to the LHC. The known bottlenecks must be treated by upgrading the equipment, and the suspected ones must be further studied. In the SPS, this includes increasing the peak RF power capability, reducing the impedance of the kickers and searching for other impedance sources. The future programme of consolidation of the SPS magnets (section 2.1), if decided, may provide the opportunity to improve impedance and reduce the electron cloud generation by modifying the vacuum chamber.

Studies in the SPS will help confirming the interest of a new ~50 GeV synchrotron replacing the PS.

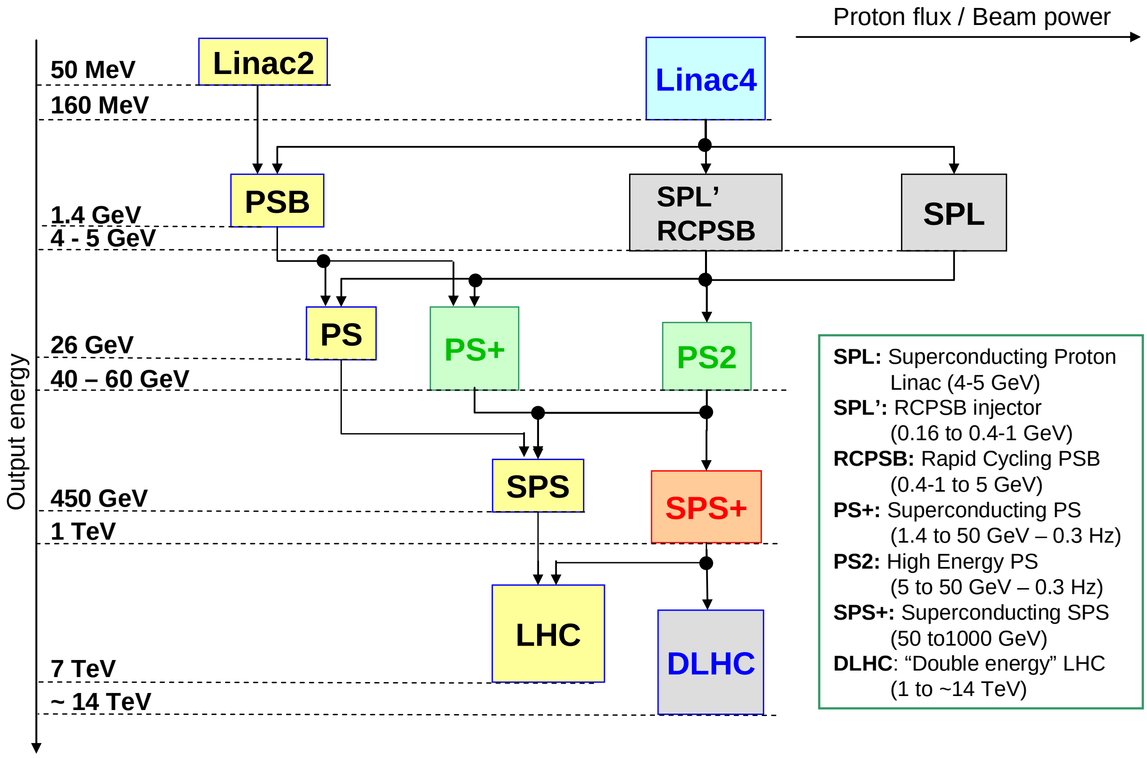

Figure 2: Evolution of the accelerator complex

In the medium term, Linac4 should be available to remove the bottleneck at injection in the PSB. This will make possible the regular delivery of the ultimate beam to the LHC, reduce its filling time and positively contribute to the overall reliability of the injector complex. To benefit from these improvements already in 2011, Linac4 construction has to start in 2007.

The replacement of the PSB has to be planned in the long term to get the maximum benefit from the PS successor. It is however not considered as crucial for the LHC, and its main characteristics will most probably be defined by the needs of other physics facilities concerning e.g. radio-active ions (EURISOL) and/or neutrinos. A Superconducting Proton Linac (SPL) is today the most promising accelerator for such purposes in the CERN context. A decision in that respect will have to wait until the future of these new facilities at CERN is clarified.

For the upgrade of the magnets in the LHC interaction regions, and to secure the presence of spare low-beta quadrupoles, an intermediate solution should be available as soon as possible and in any case before 2015. Due to the long lead time, the Nb-Ti technology is the most appropriate for these magnets whose development and construction should start as soon as possible. Such magnets would allow for a moderate luminosity increase, probably up to 3-4×10^{34} cm^{-2} s^{-1}. The development of Nb_3-Sn magnets is necessary to get the full benefit of a reduced β* of 0.25 m.

Experience with commissioning and running-in will help determine the difficulty of operating with 450 GeV injection energy and the relative merit of building a new 1 TeV injector for the LHC.

4.4 R & D

Because of the long lead time associated with it, R & D has to begin quickly for (i) the superconducting high field magnets for the LHC Interaction Regions, (ii) the fast cycling magnets that may be needed for the superconducting successors of the PS (50 GeV PS+) and/or of the SPS (1 TeV SPS+), (iii) the superconducting cavities that may be used in a superconducting linac replacing the PSB (SPL) and (iv) the high power targets in case a new facility for radio-active ions and/or neutrinos has to be built at CERN.

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References

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APPENDIX

LHC nominal and ultimate beam characteristics (see ref. [4], Vol.3 chapter 2)

		Injection	**Collision**
Energy	[GeV]	450	7000
Luminosity nominal ultimate	[$cm^{-2}s^{-1}$]		10^{34} 2.3×10^{34}
Number of bunches		2808	
Bunch spacing	[ns]	24.95	
N_b intensity per bunch nominal ultimate	[p/b]	1.15×10^{11} 1.70×10^{11}	
Beam current nominal ultimate	[A]	0.58 0.86	
ε_n(transverse emittance, rms, normalised), nominal & ultimate	[µm]	3.5	3.75
Longitudinal emittance, total Bunch length, total (4σ) Energy spread, total (4σ)	[eVs] [ns] [10^{-3}]	1.0 1.7 1.9	2.5 1.0 0.45