PLANS for upgrading the CERN proton accelerator complex



2008 J. Phys.: Conf. Ser. 110 112003

(http://iopscience.iop.org/1742-6596/110/11/112003)

# PLANS FOR UPGRADING THE CERN PROTON ACCELERATOR COMPLEX

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**Abstract**. With the construction of the Large Hadron Collider (LHC) in its final phase at CERN, it is now time to prepare for increasing its performance as much as possible and for preparing for the future needs of physics. A basic plan has been proposed by the working group on "Proton Accelerators of the Future", using the input from an ad'hoc physics working group looking after "Physics Opportunities with Future Proton Accelerators". Apart from upgrades in the LHC itself, mainly in the optics of the insertions, the proposal is to renew the injector complex and significantly improve its characteristics. 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) with a ~4 GeV superconducting proton linac (SPL) as injector. The SPS itself will be upgraded for injection at 50 GeV and for better performance with high brightness beams. These proposals will be described as well as their potential for other uses like a neutrino facility.

## 1. Introduction

The construction of the LHC is finishing and the main experiments are planned to start data taking with proton beams during the year 2008. The rate of increase of the integrated luminosity is the first priority of the physics community [1]. It depends upon the average luminosity during a coast for physics, the duration of a coast and the time spent without coast.

- The average luminosity results from the beam characteristics and from the optics of the interaction regions (β*). The LHC has been built to reach a peak luminosity of $10^{34}cm^{-2}s^{-1}$ with the nominal parameters shown in the first line of table 1 which the existing accelerators have been adapted to be capable of delivering [2]. To go beyond this nominal luminosity, various schemes are being considered [3] which combine improved beam parameters requiring major changes in the injectors and new designs of the interaction regions (table 1).
- The duration of physics coasts should be governed, after a few years, by the luminosity lifetime which varies inversely to the peak and average luminosity.
- The time spent without coast is expected to be dominated by faults and reliability problems in the injectors. This is a worrying issue with the present injector complex which has no performance margin when delivering the nominal beam and which contains numerous weak and old components (e.g. PS magnets and main power supply, RF systems etc.).

 

For these reasons, an ambitious plan of refurbishment of the injector complex has been proposed in 2006 [4], taking into account the need to maintain a diversified physics programme at CERN [1, 5].

**Table 1.** LHC beam characteristics at 7 TeV.

| Scenarios | Bunch spacing [ns] | Protons per bunch [$10^{11}$] | Beam current [A] | β* [m] | Crossing angle [μrad] | Peak luminosity [$10^{34}$cm$^{-2}$s$^{-1}$] | Luminosity lifetime [h] |
|---|---|---|---|---|---|---|---|
| Nominal | 25 | 1.15 | 0.58 | 0.55 | 285 | 1 | 15 |
| Ultimate | 25 | 1.7 | 0.86 | 0.5 | 315 | 2.3 | 8.5 |
| Separation dipoles close to the IR | 25 | 1.7 | 0.86 | 0.08 | 0 | 15.5 | 2.2 |
| Large Piwinski parameter | 50 | 4.9 | 1.22 | 0.25 | 381 | 10.7 | 4.5 |

## 2. Future injector complex

The present accelerators deal with multiple types of particles and supply beam to numerous experiments (see layout in figure 1). In the case of the proton beam for LHC [2], it is first accelerated to a kinetic energy of 50 MeV in the linear accelerator called Linac2. It is then accumulated by "transverse betatron stacking" successively in the 4 rings of the PSB synchrotron. After acceleration to 1.4 GeV kinetic, it is transferred to the PS synchrotron. It takes 1.2 s and two PSB acceleration cycles to get the 6 required bunches circulating at injection energy in the PS. During the acceleration cycle in the PS, these bunches undergo "beam gymnastics" and are transformed into 72 bunches spaced by 25 ns and filling 6/7 of the circumference. At a kinetic energy of 25 GeV they are transferred into the SPS. After having received up to four pulses from the PS, the SPS accelerates to 450 GeV and sends the beam to the LHC, filling alternately both of its rings.

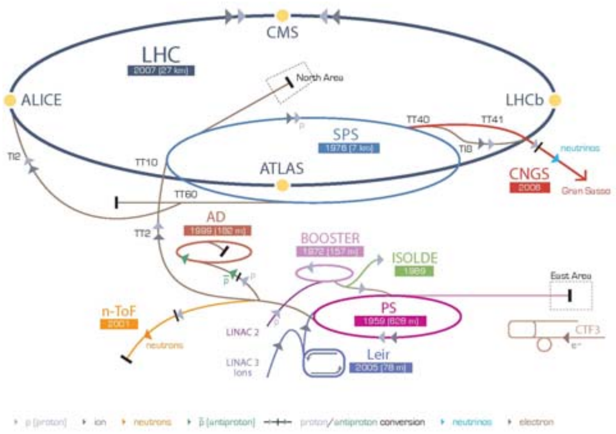


**Figure 1.** CERN accelerator complex.
- LHC: Large Hadron Collider
- SPS: Super Proton Synchrotron
- PS: Proton Synchrotron
- AD: Antiproton Decelerator
- LEIR: Low Energy Ion Ring
- LINAC: Linear Accelerator
- CTF3: CLIC Test Facility
- CNGS: CERN ν to Gran Sasso
- ISOLDE: Isotopes Separation on Line n-ToF: neutrons Time of Flight

The proposed future proton accelerators are sketched in figure 2, together with the present ones. A "successor" is foreseen for each existing machine, reaching a higher energy and benefiting from the knowledge acquired in the design of particle accelerators during the last 40 years. For the PSB, the PS and to a lesser extent the SPS, increasing the injection energy is dictated by the incoherent space charge tune spread $\Delta Q_{SC}$ which limits beam brightness ($N_b/\varepsilon_{X,Y}$) and scales like:

$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \frac{R}{\beta\gamma^2} \tag{1}$$

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 $\beta$ and $\gamma$ are classical relativistic parameters.

With injection at 160 MeV from the new Linac4 (a factor of 2 in $\beta\gamma^2$ with respect to 50 MeV), the PSB will be able to deliver beam with twice the brightness and, therefore, to fill in a single pulse the

PS with the proper beam for LHC. To improve the situation in the SPS whose injection energy is also uncomfortably close to transition, the new PS2 will provide beam at 50 GeV. The size of a 50 GeV synchrotron and the requirements to reliably cope with the maximum brightness ever necessary for SLHC or DLHC translate into an injection energy of ~4 GeV.

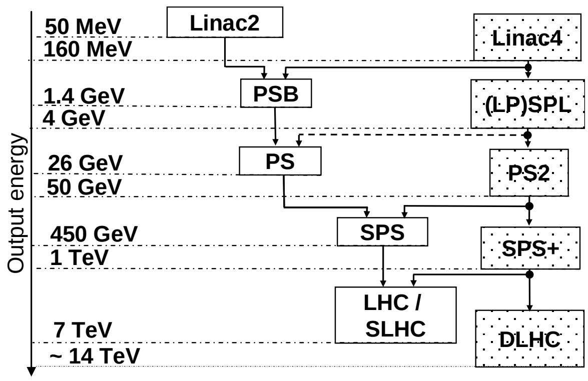


**Figure 2.** Present and proposed future accelerators:
- Linac4: 160 MeV H- linac
- (LP)SPL: (Low Power) Superconducting Proton (H-) Linac (~5 GeV)
- PS2: new proton synchrotron (~50 GeV)
- SPS+: superconducting SPS (~1 TeV)
- SLHC: LHC with luminosity upgrade
- DLHC: double energy LHC.

Although a Rapid Cycling Synchrotron could be considered as injector for PS2, a superconducting linac presents significant advantages in the CERN context [6], especially because of its flexibility and its capability to evolve towards the very large beam power expected, for example, for neutrino physics in the future [7]. Therefore the Low Power version of a Superconducting Proton Linac is the baseline solution for the PS2 injector.

In the long term, the physics community [1] has a declared interest in collisions at higher energies. The replacement of all LHC magnets by higher field units (provided that R & D progresses sufficiently) will undoubtedly be an attractive option. This energy-upgraded version of LHC (DLHC) will require an injection energy of approximately 1 TeV, which could be obtained with a synchrotron equipped with superconducting magnets in the SPS tunnel (SPS+). This scenario provides an additional argument for the higher energy of PS2.

## 3. Stages of implementation

For economical reasons as well as for minimizing the disturbance to the physics programme, implementation has to be staged. The lay-out of the full accelerator has been studied to locate immediately every machine at the most appropriate place and to progressively adapt the infrastructure (buildings, roads, water, electricity, cryogenics …) for the long term (figure 3).

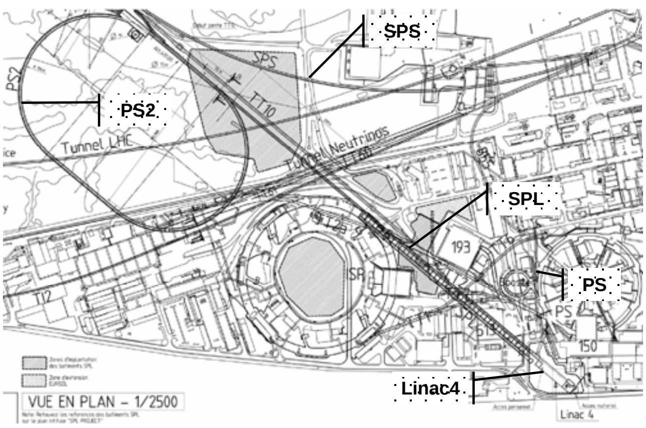


**Figure 3.** Layout of the new complex of injectors

### 3.1. Period 2008-2011

During the next four years, Linac4 [8] will be built, (LP)SPL, PS2 and the necessary improvements of the SPS will be designed, and R & D for the upgrade of the LHC insertions will take place. Linac4

Journal of Physics: Conference Series **110** (2008) 112003 doi:10.1088/1742-6596/110/1/112003

beam characteristics are summarized in table 2. It will be equipped with extensive capability for precisely tailoring the density and time structure of the beam accumulated in the PSB. Longitudinally, a fast chopper at 3 MeV will control the time structure and dedicated RF cavities at 160 MeV will help shape energy and energy spread. Transversely, the $H^-$ ions will be accumulated by charge exchange injection, allowing a precise control of transverse densities.

**Table 2.** Linac4 beam characteristics

| | |
|---|---|
| Ion species | $H^-$ |
| Beam energy (kinetic) | 160 MeV |
| Bunch frequency | 352.2 MHz |
| Maximum repetition rate | 2 Hz |
| Beam pulse duration | 0.4 ms |
| Chopping factor (beam on / total time) | 62 % |
| Average current during the beam pulse | 40 mA |
| Number of particles per pulse | $10^{14}$ |
| Transverse emittances | 0.4 mm mrad |

When it replaces Linac2 in 2012, Linac4 will provide the following benefits:

- Higher beam performance with lower beam loss and irradiation, thanks to the efficiency of the painting schemes. A single PSB cycle will be sufficient to fill the PS, resulting in a simpler and faster filling of LHC. The maximum intensity per pulse from the PSB should increase by up to a factor of 2, which will be of benefit to ISOLDE users.
- More beam pulses from the PSB available for other users (ISOLDE or PS fixed target).
- Savings in resources by stopping Linac2.

### 3.2. Period 2012-2016

Before the end of 2011, the design of the new accelerators, of the SPS improvements and of the upgrade of the LHC insertions should be clearly defined and their cost evaluated. Combined with the physics results from the first years of LHC operation which will determine the interest of a luminosity upgrade, these will allow for a properly motivated decision. Construction of the new accelerators could then begin in 2012 simultaneously with a progressive upgrade of SPS. Beam commissioning could then take place in the course of 2016, without interfering with the on-going physics programme. The final modifications of the SPS and the upgrade of LHC will necessitate a one year interruption of physics which can partly overlap with the commissioning of the new accelerators.

The LPSPL and SPL [9] will use Linac4 as low energy front end and will therefore share a number of its features, such as $H^-$ ions, bunching frequency, chopping capability and small transverse emittances. Their other essential beam characteristics are given in table 3. Table 4 describes PS2 in comparison with the present PS. Once these new injectors are in operation, all the potential of the scenarios implemented to upgrade the luminosity in the LHC itself will be usable as a result of the brightness of the beam available at injection in the collider.

**Table 3.** LPSPL and SPL beam characteristics

| | LPSPL for SPS & LHC | SPL for ν |
|---|---|---|
| Beam energy (kinetic) | 4 GeV | 5 GeV |
| Beam power | 0.19 MW | 4 MW |
| Maximum repetition rate | 2 Hz | 50 Hz |
| Beam pulse duration | 1.2 ms | 0.4 ms |
| Average current during the beam pulse | 20 mA | 40 mA |
| Number of particles per pulse | $1.4 \times 10^{14}$ | $10^{14}$ |
| Physical length | 460 m | 535 m |

Moreover, because of the simplified scheme of generation of the beam (less pulses for filling the SPS, no more beam gymnastics in PS2 and faster filling time of LHC) and because the injectors will be new, their reliability should be drastically improved which will be especially crucial to minimize lost time between physics coasts at very high luminosity.

Beyond these advantages for the LHC, an order of magnitude higher proton flux at 50 and 4 GeV and a new range of possibilities will be available for other users. Fixed target experiments in the SPS (e.g. neutrinos to GranSasso [10]) could also significantly profit. In the longer term, the potential of the LPSPL to be upgraded to a multi-MW SPL could be used for the proton driver of a ν factory [7, 11] or for a EURISOL-like [12] facility.

**Table 4.** PS2 beam characteristics (with comparison to the PS)

| | PS2 | Present PS |
|---|---|---|
| Injection energy (kinetic) | 4 GeV | 1.4 GeV |
| Extraction energy (kinetic) | 50 GeV | 13 to 25 GeV |
| Circumference | 1346 m | 628 m |
| Maximum number of protons/bunch for LHC (25 ns) | $4 \times 10^{11}$ | $1.7 \times 10^{11}$ |
| Maximum number of protons/pulse for fixed target | $1.2 \times 10^{14}$ | $3.3 \times 10^{13}$ |
| Maximum energy per beam pulse | 1000 kJ | 70 kJ |
| Minimum repetition period at highest energy | 2.5 s | 2.4 s |
| Maximum effective beam power | 400 kW | 60 kW |

## 4. Conclusion

Well aligned with the European strategy for particle physics [13], the proposals described in this paper will provide the capability to maximize the physics potential of the LHC while maintaining an as broad as possible physics programme at CERN. During the design of the future accelerators in the course of the next four years, the attempt will be made to take into account as much as possible the specific needs of additional physics requests.

## References

[1] Blondel A, Camilleri L, Ceccucci A, Ellis J, Lindroos M, Mangano M and Rolandi G 2006 Physics Opportunities with Future Proton Accelerators at CERN *CERN-PH-TH/2006-175*
[2] Benedikt M, Collier P, Mertens V, Poole J and Schindl K editors 2004 LHC Design Report Vol. III *CERN-2004-003*
[3] Bruning O 2007 LHC Challenges and Upgrade Options *These proceedings*
[4] Benedikt M, Garoby R, Ruggiero F, Ostojic O, Scandale W, Shaposhnikova E and Wenninger J 2006 Preliminary accelerator plans for maximizing the integrated LHC luminosity *CERN-AB-2006-018-PAF*
[5] Benedikt M, Garoby R, Ruggiero F, Ostojic O, Scandale W, Shaposhnikova E and Wenninger J 2006 Potential for neutrino and radioactive beam physics of the foreseen upgrades of the CERN accelerators *CERN-AB-2006-019 PAF*
[6] Garoby R, Benedikt M, Fabich A, Gerigk F 2007 Comparison of Options for the Injector of PS2 *CERN-AB-2007-014-PAF*
[7] Baldini A et al 2006 Beams for European Neutrino Experiments (BENE) *CERN-2006-005*
[8] Gerigk F, Vretenar M (editors) 2006 Linac4 Technical Design Report *CERN-AB-2006-084 ABP/RF*
[9] Gerigk F (editor) 2006 Conceptual design of the SPL II *CERN-2006-006*
[10] Meddahi M, Shapishnikova E 2007 Analysis of the maximum potential proton flux to CNGS *CERN-AB-2007-013-PAF*
[11] Aiba M 2007 Compressor Lattice Design for SPL Beam *CERN-AB-Note-2007-034 BI*
[12] EURISOL report 2004 http://www.ganil.fr/eurisol/Final_Report/EURISOL-REPORT.pdf
[13] Peach K J chairman, 2006 European Strategy for Particle Physics *CERN DOC-11347*