SCENARIOS FOR UPGRADING THE LHC INJECTORS

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Abstract

The presence of a powerful accelerator complex that could serve as injector has been instrumental in the decision to build the LHC at CERN. This existing complex has now confirmed its capability, having demonstrated that it is able to deliver beam with the nominal characteristics as well as numerous other types of beams which will be essential for tuning-in, commissioning and operating the future collider for physics in its first years. However it is also clear that the existing LHC injectors will not be able to deliver beam with the ultimate characteristics and that they suffer from reliability problems due to their age. An analysis has therefore been done by the working group in charge of "Proton Accelerators of the Future" (PAF) to determine a logical evolution of the accelerator complex, considering the needs of LHC and of the other potential future physics experiments at CERN. As a result, scenarios for a staged upgrade have been proposed, involving the progressive replacement of all the low energy accelerators [1].

PHYSICS NEEDS

The CERN accelerators traditionally serve a large variety of physics experiments, delivering beams over all their energy range to a set of experimental areas (e.g. ISOLDE, PS East Area, SPS North Area, CNGS …: see Fig. 1). Although the LHC experiments will continue to be given the highest priority in the future, the diversity of the physics programme will have to be maintained.

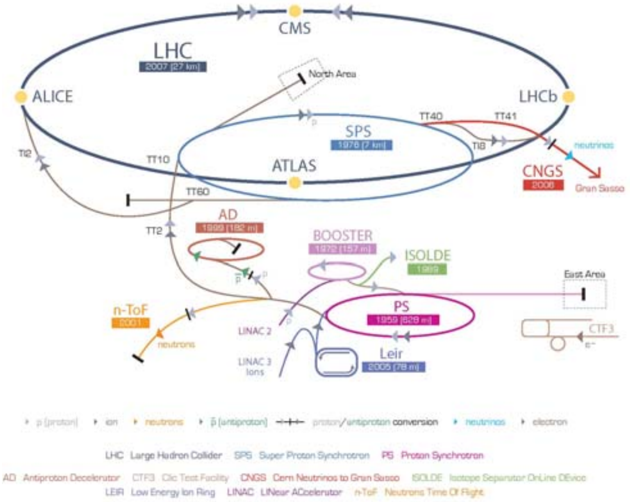

Figure 1: CERN Accelerator complex

This has been taken in consideration by the working group on "Physics Opportunities with Future Proton Accelerators" (POFPA) [2], which has clearly stated that (i) physics with the LHC is the highest priority (including upgrades in luminosity and possibly in energy), (ii) preparing for a forefront neutrino oscillation facility is the second priority and that (iii) experiments on other physics subjects should be encouraged to make use of the facilities elaborated for the first two priorities.

STATUS OF THE LHC INJECTORS

LHC design requirements

The main beam characteristics required by the LHC are summarised in the first 2 lines of Table 1. The nominal (resp. ultimate) intensity per bunch is needed for the LHC to reach its nominal (resp. ultimate) peak luminosity of 10^{34} $cm^{-2}s^{-1}$ (resp. 2.3×10^{34} $cm^{-2}s^{-1}$) [3].

Table 1: LHC beam characteristics at 7 TeV

Scenario	Bunch spacing [ns]	Protons / bunch [10^{11}]	Transverse emittance [mm.mrad]	Intensity factor at PS injection
Nominal	25	1.15	3.75	**0.68**
Ultimate	25	1.7	3.75	**1**
2 × ultimate & 25 ns spacing	25	3.4	7.5	**2**
~3 × ultimate & 50 ns spacing	50	4.9	3.75	**1.44**

Performance of the injectors

The necessary modifications to prepare the CERN accelerators for becoming the injectors of LHC have now all been implemented. The achievable beam characteristics have been measured and the main obstacles towards higher performance are identified. The result is the following:

- The first two accelerators (Linac2 and PSB) almost meet the ultimate beam characteristics. Three out of the 4 PSB rings are able to deliver 2.04×10^{12} protons within transverse emittances of 2.5 mm.mrad. In the absence of beam loss, this converts precisely into 12 bunches of 1.7×10^{11} protons, which is the ultimate goal.
- The sophisticated beam manipulations in the PS are well adjusted and reproducible. However, because of beam loss at multiple places in the cycle, the maximum intensity at ejection to the SPS has never exceeded 1.4×10^{11} p/b (within transverse emittances of 3 mm.mrad).
- Also because of beam loss, the SPS, after scrubbing to reduce the secondary electron yield of the vacuum chamber, is only able to bring up to 450 GeV the nominal type of beam made up of 4×72 bunches with

$1.15{\times}10^{11}$ p/b (within transverse emittances of 3.5 mm.mrad).

The main identified bottlenecks are linked to space charge at injection in the PSB and in the PS. The present solution of pulsing the PSB twice just allows meeting the LHC ultimate requirements out of the PSB, but it forces the PS to keep the first injected beam for the duration of a full PSB cycle (1.2 s) in the presence of a very large space charge. Other known difficulties are linked to electron clouds and impedance in the PS and SPS. Moreover, the fact that the maximum beam energy of the PS is uncomfortably close to transition in the SPS is a suspected source of troubles.

Another important observation, especially obvious in 2006, is that the reliability of the accelerators is degrading, mostly because of the age of large and expensive hardware (examples of problems encountered in 2006: aggravation of vacuum leak in the Linac2 tanks, isolation of main PS dipoles, rotor failure in the PS generatrix, water leaks on the main SPS dipoles…).

Needs of SLHC

Many different scenarios have been considered so far for increasing the luminosity in LHC beyond the ultimate level (SLHC). They are based on combining a complete redesign of the optics in the interaction regions (mostly to achieve a smaller β^*) with important changes in the beam characteristics (mostly bunch intensity and bunch spacing). The three last lines in Table 1 are typical examples [4]. For the injectors, which are space charge dominated, these beams are characterized by the intensity circulating in the PS at injection (last column in Table 1). The "ultimate" beam characteristics (intensity factor of 1) can be sufficient if an "aggressive" optics is implemented (dipoles inside the detector and β^* reduced to 8 cm). Doubling the intensity per bunch ("2×ultimate & 25 ns spacing") is another possibility corresponding to an intensity factor of 2. Tripling the intensity per bunch and dividing by two the number of bunches is considered as the most promising option today, and it has an intensity factor of 1.44.

Conclusion

In conclusion, the injector complex is able to provide the nominal type of beam at injection in the LHC, but it cannot provide the ultimate beam and it will fall short of the needs of the future luminosity upgrade. Moreover, the age of many components will undoubtedly be detrimental to the availability of the beam, and hence negatively impact on the integrated luminosity accumulated every year. This effect will become more and more disturbing as the LHC gets better known and tuned.

INJECTORS UPGRADE PLANS

The present status of the LHC injectors lead the PAF workgroup to recommend the construction of new accelerators, with the goal of meeting the foreseen needs of LHC and SLHC, as well as of offering attractive performance for other potential future needs of physics with neutrinos and/or radio-active ions [5].

Upgraded injector complex

The present and proposed future accelerators are sketched in Figure 2.

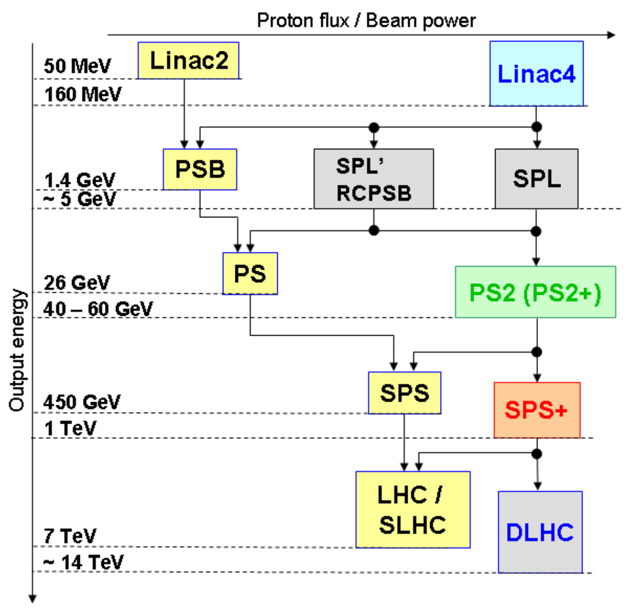

Figure 2: Present and proposed future accelerators
Linac4: 160 MeV H- linac
SPL: Superconducting Proton (H-) Linac (~5 GeV)
SPL': **RCPSB** injector (0.4-1 GeV)
RCPSB: Rapid Cycling **PSB** (~5 GeV)
PS2/PS2+: high energy **PS** (~50 GeV)
SPS+: Superconducting **SPS** (~1 TeV)
SLHC: **LHC** with luminosity upgrade
DLHC: Double energy **LHC**

Linac4 [6] is proposed as the future injector of all proton accelerators. First used with the PSB, it will reduce space charge effects by a factor of two at injection because of the higher beam energy of 160 MeV. Capture efficiency is expected to be very high (~98 %) thanks to the charge exchange H^- injection process and to the time structure of the beam pulse which will be chopped at the PSB RF frequency. In a later stage, Linac4 could be the front-end of a higher energy linac (SPL or SPL').

PS2 (PS2+) is the future successor of the PS. In its present version, it is twice the size and the energy of its predecessor. Based on state-of-the-art knowledge in accelerator physics and technology, it will be designed to comfortably meet the most extreme needs of LHC and to ease the operation of the following synchrotron. Although the benefits of the higher energy of PS2 for the SPS are quite clear, an optimization has to be made to determine it precisely, taking also into account the potential needs of the SPS+. A preliminary study is being made, to assess the relative merits of superconducting (PS2+) with respect to normal conducting magnets (PS2) in this context.

For optimum performance, the PS2 (PS2+) will need a new ~5 GeV injector, designed for that purpose. Two possibilities can be considered: a Rapid Cycling Synchrotron (RCPSB) which will require a linac injector of more than 0.4 GeV, or a high energy linac like the proposed Superconducting Proton Linac (SPL) [7]. Because of its flexibility and its unique potential for future facilities for neutrinos and radioactive ions the SPL is nowadays the preferred option.

The SPS will have to be upgraded to make the best use of the beam provided. It will however remain limited to a maximum beam energy of 450 GeV. To increase it to ~1 TeV a new synchrotron equipped with superconducting magnets (SPS+) could be installed in the SPS tunnel. Such a new injector would undoubtedly be very beneficial to the LHC and will be mandatory if the LHC itself is one day equipped with higher field dipole magnets to reach a much higher energy (DLHC).

Stages of implementation

In a first stage, Linac4 will be built to replace Linac2 and double the beam brightness of the PSB. The PSB will therefore become able to deliver the ultimate type of beam for the LHC in a single pulse instead of two. The much shorter injection flat porch in the PS will reduce beam loss and shorten the PS cycle from 3.6 to 2.4 s. The single injection will considerably simplify operation and increase reliability. The SPS will benefit from a faster filling (7.2 s instead of 10.8 s) and thus the LHC. The improved reliability should result in a reduction of the time interval between fills in the LHC. The increased brightness of the PSB beam will make it possible to investigate the capability of the rest of the injectors to operate at or beyond the ultimate LHC beam characteristics.

PS2 (PS2+) will be built in a second stage, preferably simultaneously with its own injector. The beam characteristics required for the LHC luminosity upgrade will be available at injection of the SPS. The higher injection energy and the upgrades of the SPS will be determined to meet the goal of accelerating this beam to 450 GeV and making it available to the LHC. While the new injectors will be built, the hardware for the luminosity upgrade of the LHC itself will be prepared. During the long stop required to implement the changes in the LHC tunnel, the SPS will be modified and commissioned with beam from the new accelerators. Therefore the commissioning of SLHC should immediately benefit from a well adjusted injector cascade.

The implementation of the SPS+ could take place in a last stage. Considering that the SPS has been built in the mid-70s, its replacement by a modern synchrotron will perfectly make sense during the next decade, and it is foreseeable that physics prospects will advocate for a higher beam energy and hence for the use of superconducting magnets. The decision to build SPS+ could also be driven by progress in the R & D for high field superconducting magnets for the DLHC.

OTHER BENEFITS OF THE ACCELERATORS UPGRADES

Although tailored to fit the needs of the LHC upgrades, the proposed new accelerators have the potential to extend the reach of physics experiments, especially for neutrinos and radioactive ions. Table 2 summarises these possibilities.

Table 2: Physics potential of the successive accelerators upgrades

	Linac4	**SPL PS2**	**SPL PS2 SPS+**
Perf. of LHC injectors for SLHC	Ultimate beam from PS	> ultimate beam from SPS	Highest performance LHC injector
Perf. of LHC injectors for Higher energy LHC	-	-	Adequate
Conventional ν beam	Marginal SPS improv.	Higher flux from SPS [9] Very high flux from SPL (4 MW)	Higher flux from SPS [9] Very high flux from SPL (4 MW)
ν from beta beam facility	-	Adequate	Adequate
ν factory	-	Adequate (4 MW from SPL)	Adequate (4 MW from SPL)
k and μ	Marginal SPS improv.	Higher flux from SPS [8] ~ 200 kW from PS2	Higher flux from SPS [8] ~ 200 kW from PS2
Radioactive ions (EURISOL)	-	Adequate (5 MW from SPL)	Adequate (5 MW from SPL)

Neutrinos

After the second stage of upgrade of the injector complex (PS2 and its injectors + adequate improvements of the SPS), the SPS will be able to deliver a significantly larger (> 2×) flux of protons for fixed target physics [8]. The conventional neutrino beam towards Gran Sasso could immediately benefit from this improvement [9]. At lower energy, the SPL with its capability to provide more than 4 MW of beam power, can be the core part of a proton driver for many different types of facilities. A low energy “superbeam” can be obtained by combining the SPL with an accumulator ring to compress the beam pulse to a few microseconds. The resulting low energy neutrino beam could be exploited in a large water Cherenkov detector located at ~150 km [10]. The SPL is also adequate for a neutrino factory, when associated with a set of two fixed energy rings: an accumulator to reduce the beam pulse to a few microseconds and a compressor to reduce the length of the bunches to the required value

[11]. In case a neutrino facility based on beta beam is preferred, the SPL would be an adequate driver to generate the beta-unstable radioactive nuclei [11].

Radioactive ion beams

The SPL would be an excellent driver for an ISOL-like radioactive ion beam facility of the next generation, as studied in the frame of the EURISOL design study [12]. The high beam power potentially available from the SPL would be well matched for indirect production of neutron-heavy nuclei by spallation neutrons from an irradiated target. If a neutrino factory must be simultaneously accommodated, the SPL beam power could be upgraded to 9 MW by upgrading the infrastructure (electrical and water supply, cryogenic cooling capacity).

Other physics experiments

The study of rare kaon decays could benefit from the higher proton flux of the SPS, after the second stage of the injectors upgrade. It could also make use of the beam from PS2 which could reach ~200 kW.

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