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UPGRADE PLANS FOR THE LHC INJECTOR COMPLEX

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Abstract

Challenging beams with much higher brightness than today are required for the LHC to achieve its high luminosity objective after the year 2020. It is the purpose of the LHC Injectors Upgrade (LIU) project to achieve this result, consolidating and upgrading the existing set of synchrotrons (PSB, PS and SPS), and using the new linac presently in construction (Linac4). The anticipated beam characteristics are described and compared to the known limitations in the different accelerators. The foreseen solutions are outlined as well as the planning for their implementation.

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INTRODUCTION

The instantaneous luminosity in the LHC (L_{LHC}) can be expressed as:

$$L_{LHC} = \left(\frac{\gamma}{4\pi} \frac{1}{\beta^*} f_{rev} F \right) \cdot \left(n_b \frac{N_b^2}{\varepsilon_n} \right)$$

where γ is the usual relativistic factor, β^* the betatron function at the Interaction Point, f_{rev} the beam revolution frequency, F a form factor depending upon the geometry of the bunch crossing, n_b the number of bunches per ring, N_b the number of protons per bunch and ε_n the normalised transverse emittance of the beam (assumed round).

The second term in this formula shows that, independently of the modifications in the LHC itself, the instantaneous luminosity directly depends upon the characteristics of the injected beam. Moreover, maximizing the integrated luminosity requires the highest possible circulating current in the collider (proportional to $n_b N_b$) and hence from the injectors [1].

The excellent performance of the present accelerator complex (1.6 10^{11} p/b with 50 ns bunch spacing within emittances of 2 mm.mrad at ejection from the SPS) has been an essential ingredient to the results obtained so far in the LHC. To reach the baseline goal of the High Luminosity Upgrade of the LHC (HL-LHC) (2.2 10^{11} p/b with 25 ns bunch spacing within emittances of 2.3 mm.mrad at ejection from the SPS, assuming no beam loss and 10 % blow-up in the LHC) [1], the injected beam must be improved by a factor 3.4 in terms of $\left(n_b \frac{N_b^2}{\varepsilon_n} \right)$.

The LHC Injectors Upgrade (LIU) project is ultimately aiming at these characteristics by acting upon the known limitations of the different accelerators, together with large scale consolidation [2, 3]. For that purpose, the present 50 MeV proton linac (Linac2) will be replaced with a 160 MeV H^- linac (Linac4) and extensive upgrades will be implemented in the existing synchrotrons (PSB, PS and SPS).

MAIN PRINCIPLES OF THE UPGRADE

The space charge induced tune shift in the lowest energy synchrotrons of the injection chain (PSB and PS) is proportional to $1/\beta\gamma^2 \cdot (N_b/\varepsilon_n)$. This first obvious limitation to the brightness N_b/ε_n will be addressed by increasing the injection energy from 50 to 160 MeV for the PSB, and from 1.4 to 2 GeV for the PS.

Transverse beam stability at such challenging brightness will systematically require careful optimization of the working points (PSB, PS and SPS), improved compensation of resonances and upgraded or new transverse feedbacks. Moreover, electron cloud effects in the SPS and possibly the PS will require specific actions.

In all synchrotrons, the RF systems represent another obvious limitation because of their power capability (in the case of PSB and SPS), because of their impedance for the beam (PS and SPS) and for reliability reasons (PSB, PS and SPS). All RF systems will therefore be subject to major changes or extensions, some being even planned for replacement (PSB).

Longitudinal beam stability at these unprecedented longitudinal densities is planned to be obtained with the combined effect of reduced impedances, new feedback (PS) and/or changing the momentum compaction factor with a new lattice (SPS).

A number of ageing equipment systems have to be replaced to guarantee a reliable operation during the foreseen lifetime of HL-LHC, which extends beyond 2030 (e.g. main PSB power supply). Additional safety measures (radiation shielding, interlocks, scrapers) have also to be implemented. Finally, the problems of numerous devices (e.g. heating of SPS kicker by the beam current, sparking of electrostatic septum etc.) have to be treated.

LINAC4

The new linac presently in construction (Linac4, the 4th hadron linac to be built at CERN) [4] will replace the aging Linac2 and provide beam at 160 MeV instead of 50 MeV, halving the space charge effects in the PSB. Approved by the CERN Council in June 2007, Linac4 will allow tailoring the beam in the PSB in all planes (transversely with painting thanks to the charge exchange injection and longitudinally thanks to the high speed chopper at 3 MeV).

The overall layout of Linac4 is sketched in Fig. 1.

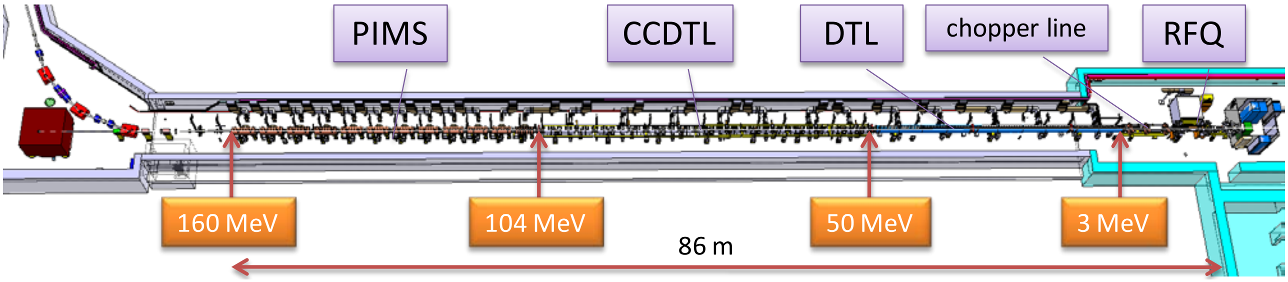

Figure 1: Linac4 layout.

Performance

Thanks to the increased injection energy, the maximum intensity in the PSB can potentially be doubled for the same space charge tune shift and within the same normalized emittances. The beam pulse delivered by Linac4 will allow exploiting this possibility at the highest rate acceptable for the PSB magnetic cycle (1.1 Hz).

Beam line Components

An H^- ion source with extraction at 45 keV is in construction and will be commissioned on the 3 MeV Test Stand during the summer. This source is designed to provide a commissioning beam and to be an intermediate step towards the cesiated RF-type source that will be used for Linac4 final commissioning and operation.

Following the source, a 3 m long 4-vane RFQ bunches and accelerates the beam to 3 MeV. The third and last 1 m long module has recently been completed with the successful brazing of the RF ports (Fig. 2). The complete RFQ with its 3 modules will be assembled in the Test Stand in June and tested with beam during the Autumn.

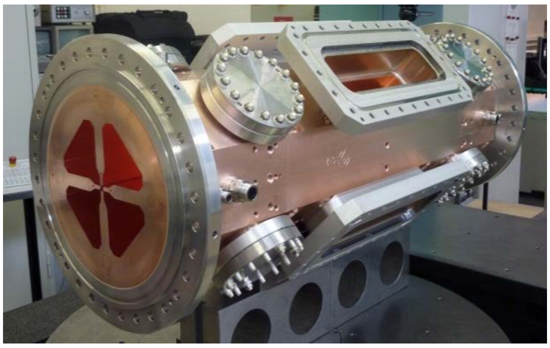
Figure 2: Third RFQ module.

The deflecting structure of the fast chopper consists of two 40 cm long meander-lines on a ceramic substrate, inserted inside a quadrupole. Driven by a pulser of 1.5 ns rise-time (10 to 90%), it allows a clean bunch selection. The deflected beam is sent on a conical dump that acts like a collimator for the non-deflected beam. Three rebunching cavities, 11 quadrupoles and diagnostic equipment complete the 3.6 m long chopper line and allow transporting, measuring and matching of the beam before injection into the DTL. The chopper line is completed and will be tested with beam before the end of 2012, as soon as the RFQ is operational. After completion of these tests, RFQ and chopper line will be transported to the Linac4 building in 2013.

A Drift Tube Linac (DTL) divided in three tanks accelerates the 3 MeV beam up to 50 MeV. Transverse focusing is provided by 108 Permanent Magnet Quadrupoles (PMQ) placed in vacuum inside the drift tubes. The DTL is based on a new mechanical design allowing precise positioning of the drift tubes inside the tank, without the need for bellows or rubber vacuum joints to align the drift tubes after assembly. The DTL structures are in fabrication in industry, in collaboration with the ESS-Bilbao project. Assembly and tuning will be done at CERN. The goal is to complete assembly of the first DTL tank in 2012.

Acceleration from 50 to 104 MeV is obtained in the Cell-Coupled DTL, made-up of 7 accelerating modules; a module is composed of three tanks housing two drift tubes each and connected by coupling cells. Focusing is provided by a combination of PMQs (between tanks) and electromagnetic quadrupoles (between modules). Construction, assembly and tuning have been taken over by a collaboration of Russian laboratories (VNIITF Snezinsk and BINP Novosibirsk). The first three modules will be delivered at CERN in September.

The Pi-Mode Structure (PIMS) section brings the beam to its final energy of 160 MeV. It consists of twelve 7-cell cavities operating in pi-mode. Construction of the cavities has started in collaboration with the Polish Institute for Nuclear Studies, with part of the electron beam welding done at FZ Jülich (Germany).

Linac4 will be terminated in a beam dump, preceded by a bending magnet which can send the beam into the 70 m long transfer line connecting to the present Linac2-PSB transfer line. A PIMS-type cavity in the line acts as a debuncher, matching the beam energy spread to the PSB acceptance.

RF and Beam Instrumentation

The Linac4 Radio-Frequency system in its initial configuration will use thirteen 1.3 MW-klystrons, from the former CERN LEP accelerator, and six new 2.8 MW klystrons. The 110 kV modulators, equipped with a HV pulse transformer and a droop compensation bouncer, can serve either one high-power klystron or two LEP-type devices. The digital Low-Level RF with feed-forward capability is derived from the LHC system. Its prototype will soon be tested in the 3 MeV Test Stand. Testing of the LEP klystrons before installation is progressing, prototypes of the new 2.8 MW klystrons are under test and modulators are in construction.

Beam diagnostics are modified versions of standard devices used in other CERN accelerators. Strip-line pick-ups are used in the 27 beam position monitors; 16 SEM-grids and 6 wire scanners are used for beam profile measurements; 15 beam current transformers measure the intensity. Additional diagnostics equipment placed on movable temporary measurement benches will be used during commissioning.

Planning

Civil Engineering is completed and infrastructure installation is in progress. Accelerator components will be installed in the tunnel between end 2012 and 2013. Between 2013 and 2014, beam commissioning will take place at progressively increasing energy. From the end of 2014, Linac4 will be available as a back-up for supplying 50 MeV protons in case of Linac2 failure, or as a source of 160 MeV H^- as soon as the PSB is ready.

PSB

Despite significant advantages, the alternative option of replacing the PSB with a new Rapid Cycling Synchrotron has not been retained, mainly because of cost and limitations for high intensity in the PS [5].

H^- Injection and Operation with Linac4

The injection process has to be changed from the present multi-turn betatron injection using a horizontal injection septum to charge-exchange injection using a stripper foil [6]. This scheme will make it possible to tailor the particle distribution, for example for producing flat rather than round beams to reduce losses in the PS. The equipment to be modified include the beam separation system at the end of the Linac4 transfer line (distributor and vertical septum), as well as a number of magnets. In the PSB itself, the injection periods have to be completely rebuilt, removing the horizontal injection septum and replacing it by a stripper foil mechanism along with the associated bumper magnets, unstripped ion beam dump, diagnostics and other equipment. As space is especially tight in the PSB with its 4 superimposed rings, the replacement of two main dipoles in the vicinity of the injection point by shorter ones is therefore under study.

Two RF systems in each ring are planned to be replaced by a wideband new one based on Finemet® technology [7], pending success of the on-going test of the prototype cavity installed during the 2011/12 winter shutdown (Fig. 3). In case of unforeseen technical problems, the back-up solution will be to extensively consolidate and upgrade the existing RF systems.

New beam instrumentation is required for setting up the H^- injection (e.g. for monitoring the injected and circulating beams, the stripper foil, the partially stripped and unstripped beams etc.). Furthermore the orbit measurement system must be upgraded to allow turn-by-turn trajectory measurement in the four rings. The BLM system will be an essential part of the newly designed Linac4-PSB interlock system and must be renovated.

Figure 3: Prototype Finemet® RF system in the PSB.

The beam dump will have to be replaced to cope with the increased intensity and the 2 GeV beam energy. Installation is planned in 2013.

Many other renovations are also necessary concerning controls, electrical distribution, cooling and ventilation, radioprotection etc.

Increased Ejection Energy from 1.4 to 2 GeV

For increasing the maximum energy of the PSB from 1.4 GeV to 2 GeV, the main devices concerned are the ring magnets (especially main dipoles) and their power supplies, and all the equipment related to beam extraction, recombination and transfer to the PS [6]. The ring magnets are capable of operating at the higher field, provided that the rms current does not increase by more than 10%. The power supply of the main dipole has to be replaced by a new one using capacitors for energy storage [8]. A number of kickers and septa cannot operate at 2.0 GeV and need either replacement or modifications, notably the extraction kickers and recombination septa. 40% of the magnets in the transfer line must be changed.

Planning

Preliminary work is planned in the tunnel during the first Long LHC shutdown (LS1) in 2013-2014 to install prototypes and prepare for the connection with Linac4. The H^- injection equipment will be ready at the end of 2015 and connection will be possible during the next long enough (> 8 months) proton shutdown of the LHC. The higher brightness achievable with 160 MeV injection will be available after a beam commissioning period following the connection with Linac4. However, the bulk of the modifications (e.g. RF systems, energy upgrade etc.) will only take place during the second long LHC shutdown (LS2), presently scheduled in 2018.

PS

Increased injection energy from 1.4 to 2 GeV

Most injection elements will have to be changed, the existing ones being already today at their operational limit. A new and longer septum will replace the existing one, a new kicker will be installed and a new injection bump based on 5 magnets will be implemented. Two concepts are being investigated for the new septum, one using direct drive (Fig. 4), the other based on eddy current. The very short length available and the need to include one of the injection bumpers inside the same vacuum tank make the design very challenging.

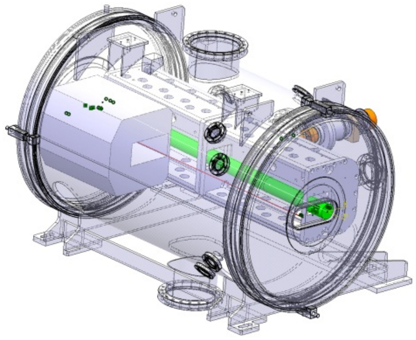

Figure 4: PS injection septum and bumper in the same vacuum tank (injected beam is in green).

Preservation of High Transverse Brightness

The Laslett tune shift of the LHC beam will be large, possibly beyond 0.3, and particles are likely to cross the integer and/or the 1/3 stop bands. Beam experiments and simulations are in progress to analyse the potential blow-up and the need for resonance compensation.

A new way of controlling the working point at low energy is under investigation, making use of the dedicated extra windings mounted on the main magnets instead of dedicated quadrupoles. Horizontal correctors do not need replacement, but the conclusion is not yet drawn for the vertical ones. New skew quadrupoles designed to operate reliably at 2 GeV will have to be installed. For all these low energy magnets, power converters will have to be replaced. An operational transverse damper will be required.

Electron cloud formation is regularly observed with the LHC beam, when bunches becomes very short just before extraction. Although no detrimental effect has yet been seen on the beam, beam experiments and simulations are being made to estimate if this will remain the case for the HL-LHC types of beams. If required, a wide band damper or the coating of the vacuum chamber could be envisaged.

Longitudinal Beam Gymnastics

As presently [9], sophisticated beam gymnastics will continue to be necessary in the PS to produce the LHC beam with the proper time interval between bunches. For that purpose, a total of 24 RF cavities are used (11 systems for 2.8 - 10 MHz; two at 20 MHz; two at 40 MHz; three at 80 MHz and six at 200 MHz). Although minimized with active feedbacks and mechanical short circuits, their impedance causes longitudinal instability and transient beam loading which limit intensity/ longitudinal density, and degrades gymnastics. To reach the HL-LHC beam characteristics, the existing feedbacks will be upgraded, and new ones will be added. In particular a new longitudinal wideband feedback using a Finemet® cavity [7] will be installed.

Additional improvements

Radioprotection shielding will be significantly increased above the injection and extraction regions where more beam losses are unavoidably concentrated.

Planning

The main work in the PS tunnel during LS1 will concern the radioprotection shielding, the wideband longitudinal damper and miscellaneous upgrades of the RF systems. The main part of the modifications (e.g. 2 GeV injection, low energy magnets, e-cloud cure etc.) will take place during LS2 (~2018).

SPS

New Transverse Tune

A new SPS optics with an integer tune of 20 (Q20) instead of 26 (Q26) has been successfully demonstrated to increase the single bunch threshold for TMCI with zero chromaticity from 1.7 10^{11} p/b to above 4 10^{11} p/b [10] and to also improve the margin for other instabilities (electron cloud, multibunch). The performance achieved with single bunch meets the requirements of HL-LHC for 25 ns bunch spacing (Fig. 5). The challenge is to reach the same level with bunch trains. The deployment of the Q20 optics is in progress especially for optimising the extraction process from the SPS and it will be used to inject beam in LHC in the course of 2012.

Upgrade of the RF Systems

Longitudinal stability of the LHC beam already requires adding 800 MHz RF voltage in “Bunch Shortening Mode” to the main 200 MHz voltage. More voltage and power being required in the future, both systems will be extensively renovated and upgraded. The 800 MHz installation will be equipped with new IOT-based amplifiers and new Low Level RF during LS1. Two new 1.4 MW power plants will be added to the 200 MHz installation. The accelerating travelling wave structures, presently organized in 4 modules fed by four 1 MW amplifiers, will be rearranged in 6 modules fed by a total of 6 amplifiers. This work will be completed at the end of LS2.

Electron Cloud

Since many years the subject of electron cloud is being studied in the SPS because of its major impact on beam performance. A cure based on coating the vacuum chamber with amorphous carbon (aC) has successfully passed all tests so far. It has been shown to suppress electron cloud [11], to be stable for several years and to be applicable to the dipoles chambers without needing to disassemble the magnet. Four full half-cells are planned to be treated during LS1.

Encouraging simulations and experimental results are being obtained for a wide band (>1 GHz) transverse feedback, under investigation with the support of US-LARP [12]. A prototype system capable to handle a few bunches at low energy will be installed during LS1. Such a solution may also be relevant for the PS and possibly the LHC.

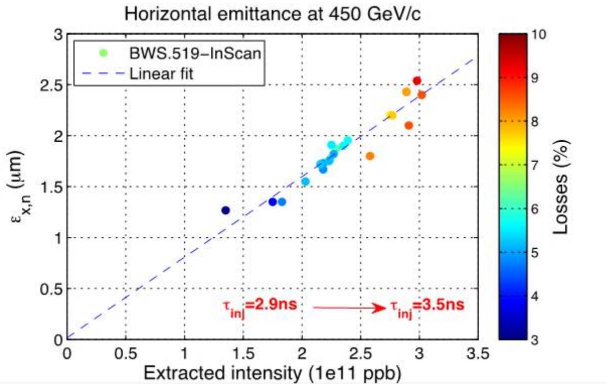

Figure 5: Single bunch characteristics with Q20 optics

Other Subjects

Action is required on multiple other fronts:

- Simulations and measurements for understanding and fighting impedance sources;
- Improvement of beam instrumentation systems to cope with the new beam parameters and higher beam brightness. Particular attention is being paid to the measurements of transverse beam size, beam current, orbit and beam loss;
- Replacement of beam intercepting and protection devices to withstand beam impact and to protect downstream elements from the increased beam energy. Redesign of the transfer lines to remove the limitation at LHC injection from losses on these devices is being studied, together with improvements to the SPS scraper system for halo shaping and to the SPS internal beam dump;
- Modification/improvement of the electrostatic septa (ZS) used for slow extraction which is sensitive to the LHC beam and which can be damaged by high intensity;
- Refinement of the vacuum sectorization of the ring to minimize irradiation to the workers, ease maintenance and avoid unnecessary exposure of the vacuum chambers to atmospheric pressure.

Planning

Work during LS1 will mostly concern prototyping (e.g. wide band transverse damper, new wire scanner etc.) and preparation for LS2. The main part of the modifications (e.g. 200 MHz RF system, electron cloud cure etc.) will take place during LS2.

PERFORMANCE ROADMAP

Progress in beam characteristics for LHC after LS1 will mostly result from new beam gymnastics [13]. Connection of Linac4 to the PSB before LS2 would be highly desirable for shortening beam commissioning after LS2 and getting experience with higher brightness beams from the PSB. However, the full benefit for the LHC will only materialize after LS2, once the main modifications (e.g. PSB to PS transfer at 2 GeV, electron cloud cures, RF system in the SPS etc.) will have been implemented.

Provided that all the foreseen measures are successful, beam characteristics at 450 GeV should hopefully be close from the HL-LHC requirements after an adequate period of setting-up and optimization (Table 1) [3].

Table 1: Comparison of performance reach for different injector upgrade hypotheses, with 25 ns bunch spacing

25 ns	N_b **[10^{11}]**	ε_n **[µm]**	$n_b \cdot N_b^2/\varepsilon_n$
HL-LHC target	2.0	2.5	1.00
2011 performance	1.1	2.8	0.20
LIU baseline	2.3	3.5	0.70
+ stretch loss/blowup	2.3	3.2	0.76
+ PS ΔQ = -0.32	2.3	2.5	1.00

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