LIU-TDR

General part

1. Introduction

Built many years ago (in 1959 for the PS), the accelerators of the injector complex were extensively consolidated and upgraded during the past decade in preparation for their role for the LHC [1, 2]. They are shown in Fig.1 (Linac2 (50 MeV), PSB (1.4 GeV), PS (25 GeV) and SPS (450 GeV) for protons, plus Linac3 and LEIR for other ions). After optimization and extensive beam scrubbing, they were able to provide beam with characteristics exceeding the nominal LHC requirements (Table 1) and decisively contributed to the excellent performance of LHC during its first run until February 2013, crowned with the discovery of the Higgs boson.



Fig. 1: CERN accelerator complex in 2012.

Their flexibility was also crucial to the LHC success. It is typically illustrated by the comparison between the beam effectively used for physics $(1.65 \cdot 10^{11} \text{ p/b} \text{ with } 50 \text{ ns} \text{ bunch spacing}$ within emittances of 1.6 µm at ejection from the SPS) and the nominal beam described in the Design Report $(1.15 \cdot 10^{11} \text{ p/b} \text{ with } 25 \text{ ns} \text{ bunch spacing}$ within emittances of 3.5 µm at ejection from the SPS) [1]. Beam with characteristics exceeding the nominal goal $(1.2 \cdot 10^{11} \text{ p/b} \text{ with } 25 \text{ ns} \text{ bunch spacing}$ within emittances of 2.6 µm at ejection from the SPS) will be used for physics during the second run of LHC, from 2015 till mid-2018, when the second Long LHC Shutdown (LS2) is scheduled. This is expected to contribute exceeding the nominal peak luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in LHC during run 2.

This is however not enough for the High Luminosity Upgrade of the LHC which aims at a levelled luminosity of $5 \cdot 10^{34}$ cm⁻²s⁻¹ with protons during run 4, after ~2022 [3]. For that purpose, the

injected beam has to be approximately twice more intense and 2.5 times more bright $(2.3 \cdot 10^{11} \text{ p/b}$ with 25 ns bunch spacing within emittances of 2.1 µm). Solutions must therefore be found and implemented in all accelerators of the LHC injector complex to reach and reliably operate at this new level of performance. The necessary work which is the core of the LHC Injectors Upgrade (LIU) project is the subject of this report.

	50 ns bunch trains at LHC injection	50 ns bunch trains at start of collisions	25 ns bunch trains at LHC injection*
Number of bunches (n_b)	1374	1374	2748
Protons/bunch (N_b)	$1.65 \cdot 10^{11}$	$1.6 \cdot 10^{11}$	$1.1 \cdot 10^{11}$
Norm. trans. emittance (ε_n) [µm]	1.6	2.4	2.8

Table 1: Beam characteri	istics in	n 2012
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* The number of 25 ns spaced bunches that the LHC could effectively accelerate was limited to 804 because of electron cloud effects [6].

Integrated luminosity with heavy ions in LHC is also expected to progress approximately by an order of magnitude during the High Luminosity era. The required upgrades in the injectors are managed by the LIU project. They are described in another report [4].

2. Present LHC Proton Injectors

2.1 Mode of operation

In the PSB and PS, the induced tune spread resulting from the high beam brightness is the main concern. It is brought to an acceptable level in the PSB by dividing the intensity per pulse by a factor two, filling the PS with 2 batches instead of a single one. This was made possible by operating the PSB on harmonic 1 and hence with a single bunch per ring. In the PS, where the first batch of bunches stays at injection energy during 1.2 s, the space charge induced tune spread has been reduced by a factor 1.5 by increasing the transfer energy from the PSB from 1 to 1.4 GeV (ratio of $\beta \gamma^2$).

The long and intense bunches delivered by the PSB are transformed in the PS into trains of bunches spaced by 25 ns (or 50 ns) before ejection, as sketched in Fig.2 (ref. [1] pp. 5-8 and 45-52 and [5]). This is obtained with quasi-adiabatic bunch splitting gymnastics which keep the beam bunched and under control of the RF. As a result, the gap without beam corresponding to the empty bucket at injection (6 PSB bunches being sent to the PS on h=7) is preserved and used for the rise-time of the ejection kicker, avoiding beam loss at ejection. Moreover, shorter bunch trains can be obtained simply with less bunches from the PSB.

Bunch splitting is done in multiple steps:

- splitting in three takes place at injection energy (1.4 GeV) combining the simultaneous use of three RF systems on harmonics 7, 14 and 21. At the end of the process, the beam is held on h=21 on which it is accelerated up to top energy.
- splitting in four takes place at 25 GeV, in two successive steps, using RF systems on h=21 and 42 for the first step, and on h=42 and 84 for the second one. Without this last step, bunch spacing is 50 ns.

In addition, the longitudinal emittance is submitted to controlled blow-ups to improve longitudinal stability, pulsing the 200 MHz cavities a few times during the cycle. Finally, a non-adiabatic bunch length reduction process is used before ejection to the SPS for reducing bunch length to \sim 4 ns which can be captured in a 200 MHz SPS bucket. In total, five families of RF systems are

necessary in the PS (3-10 MHz, 20 MHz, 40 MHz, 80 MHz and 200 MHz) to generate the proton beams for LHC.

In the SPS, the injected bunches are captured with the main RF system operating at 200 MHz. Up to 4 batches of 25 ns (or 50 ns) bunch trains from the PS are accumulated on a 10.8 s long flat bottom. Longitudinal stability is obtained adding the 4th harmonic RF (800 MHz) in Bunch Shortening mode (increasing Landau damping) and applying a longitudinal controlled blow-up during acceleration. In the transverse phase plane, the electron clouds that were limiting performance by provoking vertical instability are significantly reduced at present intensities thanks to the scrubbing of the surface of the vacuum chamber.



Fig. 2: Longitudinal bunch splitting to generate a 25 ns bunch train in the PS:
Top graphic: B field (blue) and beam current (red) during a PS cycle. Longitudinal controlled Blow-Ups (BU) are used for optimizing the gymnastics and avoiding longitudinal beam instabilities.

- Bottom pictures: 2D displays of longitudinal density at 1.4 (left) and 25 GeV (right). Time during the process is along the vertical axis. Longitudinal density is color-coded from blue (no beam) to red (maximum).

2.2 Present performance and future needs

The beam characteristics delivered at injection in the LHC before its first long shutdown in 2013 are summarized in the first column of Table 1. The corresponding brightness at injection in LHC is 20 % higher than the "nominal" value considered in the LHC Design Report [4] for a bunch spacing of 25 ns. During the first phase of operation, 50 ns spacing has however been preferred, with approximately twice the ultimate brightness and the ultimate intensity per bunch (~1.7 \cdot 10^{11} p/b) at 450 GeV. In spite of transverse blow-up in the LHC (central column in Table 1), it consistently allowed to reach 75% of the nominal peak luminosity (7.5 \cdot 10^{33} instead of 10^{34} cm⁻²s⁻¹), mostly compensating the effect of the larger physical emittance due to the reduced beam collision energy (4 instead of 7 TeV).

With these beam characteristics, the injector complex is performing as foreseen but without any margin. For the High Luminosity LHC (HL-LHC) project, which aims at accumulating ~250 fb⁻¹/year, beam characteristics in collision have to progress to the level described in Table 2. Assuming 20 % emittance blow-up and 5 % beam loss between injection and collision in LHC [3], the beam intensity required from the injectors (Table 2) has to double in the baseline case (25 ns) and the brightness shall almost triple.

	25 ns bunch trains at start of collisions	25 ns bunch trains at injection (estimate)	50 ns** bunch trains at start of collisions	50 ns** bunch trains at injection (estimate)
Number of bunches (n_b)	2748*	2748	1374*	1374
Protons/bunch (N_b)	$2.2 \cdot 10^{11}$	$2.3 \cdot 10^{11}$	$3.5 \cdot 10^{11}$	$3.7 \cdot 10^{11}$
Norm. trans. emittance (ε_n) [µm]	2.5	2.1	3	2.5

Table 2: Beam characteristics for the High Luminosity LHC project

* The filling schemes in the accelerator chain, the maximization of colliding bunches in the four experiments, and the need of non-colliding bunches will slightly reduce the number of colliding bunches in the high luminosity interaction points.

** The 50 ns scenario is a back-up, in case fundamental limitations in LHC (e.g. due to electron clouds or total intensity) are encountered with the 25 ns baseline parameters.

The presently identified limitations in the injectors are illustrated in Fig.3 together with the achieved and expected beam performances. In the coordinate system emittance versus intensity, a constant space charge induced tune spread is represented by a straight line passing through the origin. Below that line, the space charge induced tune spread is excessive. The curve corresponding to the PS is not a straight line because it takes into account the energy spread assuming a constant longitudinal emittance. The other limitations restrict the maximum intensity per bunch, which corresponds to a vertical line parallel to the Y axis. For 25 ns bunch spacing, $1.2 \cdot 10^{11}$ p/b is the maximum intensity in the SPS because of the available RF power and because of longitudinal coupled bunch instabilities. The limit due to electron clouds is nowadays beyond this intensity. For 50 ns, the main limitations result from heat dissipated in the equipment because of the beam image current and from longitudinal instabilities ($N_b < 1.7 \cdot 10^{11}$ p/b).



2012, for 25 ns (left) and 50 ns (right) bunch spacing.

Before the implementation of the upgrades described in the following part of this document, new sophisticated beam gymnastics have been proposed for generating in the PS 25 ns batches with a brightness similar to 50 ns [7]. The principle is to split the PSB beam in less bunches while keeping spacing at 25 ns. For that purpose, the batch of PSB bunches that fills most of the PS circumference at

injection is first accelerated to an intermediate energy (typically 2.5 GeV) where space charge is sufficiently reduced and then compressed into a smaller fraction of the circumference. A typical scenario is illustrated in Fig. 4:

(i) 2 consecutive batches of 4 bunches from the PSB are injected in 8 buckets of the PS on h=9,

(ii) after acceleration up to an intermediate energy of 2.5 GeV where space charge is smaller and longitudinal acceptance larger, the beam is compressed in 57% of the circumference by adiabatically increasing the harmonic number from h=9 to h=14,

(iii) bunches are merged two by two (reverse process wrt splitting in two) which results in 4 bunches on h=7,

(iv) triple splitting is finally applied, generating 12 bunches on h=21.

These 12 bunches are then accelerated up to high energy where splitting in 4 is exercised like nowadays (lower part - bottom right of Fig. 2). Compared to the present process, this "Batch Compression Merging and Splitting" (BCMS) scheme provides only 48 bunches with 25 ns spacing, instead of 72, increasing the filling time of the LHC and decreasing by approximately 10% the maximum number of bunches in the collider because of the gaps required for kickers' rise time in the SPS and LHC.



Fig. 4: 2D display (simulated) of longitudinal density in the PS during BCMS at 2.5 GeV. Time during the process is along the vertical axis. Longitudinal density is color-coded from blue (no beam) to red (maximum).

The corresponding beam characteristics at LHC injection, shown as a dashed green line in Fig. 3 (left), can potentially increase luminosity with respect to the 50 ns scheme while reducing the number of events per crossing and hence easing operation of the detectors in the experiments. The interest of the scheme will however depend upon the LHC capability to preserve the small emittances with the maximum circulating current acceptable in the collider (nominally ~0.58 A).

This scheme has already been successfully tested at the end of 2012. A much higher brightness than with the nominal scheme has been obtained, with bunches of $1.15 \cdot 10^{11}$ p/b within emittances of 1.4 µm reproducibly injected in the LHC.

3. Upgrade plan of the LHC Proton Injectors

3.1 Transverse phase plane

The primary limitation due to the space charge induced tune spread in the PSB and in the PS will again be addressed by increasing the injection energy.

In the case of the PSB, this will be obtained with a new linac (Linac4 [8]) which will provide beam at a kinetic energy of 160 MeV, doubling $\beta \gamma^2$ with respect to the present 50 MeV Linac2 [9]. The main parameters of Linac4 are summarized in Table 3. Charge exchange injection in the PSB will replace multi-turn betatron stacking, increasing the efficiency up to ~98% and providing the means to tailor the transverse distribution of protons. Painting is also foreseen in the longitudinal phase plane, to maximize capture efficiency and to optimize the longitudinal particle distribution. Operation with the same space charge tune spread $|\Delta Q_y|$ as has been achieved in the current configuration with LINAC2 (0.44), the higher injection energy is expected to allow for a brightness of $1.8 \cdot 10^{12}$ p/µm, twice the present level. With the nominal beam gymnastics and some margin for emittance blow-up, that corresponds to a brightness of 10^{11} p/µm for 25 ns bunch spacing at ejection from the SPS (resp. $2 \cdot 10^{11}$ p/µm for 50 ns).

Ion species	H
Output energy	160 MeV
Bunch frequency	352.2 MHz
Maximum repetition rate	2 Hz
Beam pulse length	400 μs
Mean pulse current	40 mA
Maximum number of particles per pulse	$1.0 \cdot 10^{14}$
Number of particles per bunch	1.14·10 ⁹
Transverse emittance	$0.4 \pi \mu m (\mathrm{rms})$

Table 3: Linac4 beam parameters

In the case of the PS, the beam injection energy will be increased from 1.4 to 2 GeV kinetic, increasing $\beta \gamma^2$ and decreasing the space charge tune spread by a factor ~1.6. This energy is attainable in the PSB [9], provided that a number of equipments are upgraded or redesigned, like the power supply for the main dipoles. Likewise, in the PS, important modifications and new equipment must be added for beam injection at 2 GeV [10] and the existing transverse damper will be renovated to avoid transverse instabilities, providing more flexibility in the choice of the tunes at low energy and hopefully stabilizing the beam on the high energy flat top.

Beyond these major changes, an extensive campaign is in progress for optimizing the transverse tunes and improving the compensation of resonances [11]. As a result, operation with larger vertical tune spreads than today is foreseen to be manageable in all synchrotrons, and especially in the PS.

In the SPS, the integer part of the tunes have recently been changed from 26 ("Q26") to 20 ("Q20"), reducing the transition energy and enhancing the slip factor $|\eta| = |1/\gamma_t^2 - 1/\gamma^2|$ to increase the thresholds of longitudinal and Transverse Mode Coupling Instabilities (TMCI) [12, 13]. With this optics, operation with a space charge tune shift in excess of 0.15 is expected to be manageable, corresponding to a brightness of ~10¹¹ p/µm at SPS ejection, matched to the capability of the upgraded PSB for 25 ns bunch spacing.

3.2 Longitudinal phase plane

The PSB is not expected to suffer from limitations in the longitudinal phase plane when providing the high brightness beams for LHC. A major renovation of the main RF systems is however required to guarantee a reliable operation during all the lifetime of the LHC and to let other users [e.g. ISOLDE] benefit from the higher intensity beams allowed with Linac4.

In the PS, the measures presently used to stabilize the beam in the longitudinal phase plane (controlled longitudinal blow-up and coupled bunch instability damper) cannot handle a bunch intensity larger than $\sim 1.7 \cdot 10^{11}$ p/bunch, both for 25 and 50 ns bunch spacing. This limitation will be addressed by a new longitudinal damper using a dedicated "broad band" cavity, aimed at bringing the instability threshold beyond $3 \cdot 10^{11}$ p/bunch. Moreover, transient beam loading in the five families of RF systems will increase with beam intensity, degrading the quality of the multiple beam gymnastics. Fast RF feedback on all high power RF systems will therefore be upgraded, and one-turn delay feedbacks will be renovated on the 3-10 MHz ferrite cavities and implemented on the other cavities. More RF voltage at 40 MHz will be installed to improve longitudinal capture efficiency in the SPS [14]. The combined effect of all these actions is expected to allow for the operational availability of $3 \cdot 10^{11}$ p/bunch at PS ejection.

In the SPS, two new 1.6 MW RF power plants will be installed, doubling the available power at 200 MHz, and the cavities will be reorganized in 6 assemblies (4 today), reducing the beam impedance. This will allow the acceleration of a beam current of up to 3 A, and 10 MV will be available on the high energy flat top, before ejection. Up to $2.3 \cdot 10^{11}$ p/bunch with 25 ns bunch spacing could then be transferred to the LHC. Longitudinal stability of the beam in the SPS is presently obtained through the combined effects of controlled longitudinal blow-up up to 0.6 eVs and 800 MHz RF voltage used in bunch shortening mode. The instability threshold will increase with the new Q20 optics thanks to the increased slip factor $|\eta|$, although this will be balanced by the smaller longitudinal emittance imposed by the reduced acceptance of the buckets. The lower impedance of the reorganized 200 MHz RF system will also be beneficial, as well as the planned renovation of the low and high power equipment of the 800 MHz system. The present estimate is that $2.3 \cdot 10^{11}$ p/bunch with 25 ns bunch spacing and $3.5 \cdot 10^{11}$ p/bunch with 50 ns should be attainable. Such intensities might require transferring longer bunches (1.6-1.8 ns) to the LHC where mitigation measures have to be studied [15].

3.3 Electron clouds

Electron cloud formation is observed in the PS on the 25 ns beam a few milliseconds before ejection and a transverse instability has repeatedly been diagnosed at the same time. Although not presently affecting performance, it is a subject of theoretical and experimental investigation to determine the risk with the future beam characteristics and to prepare cures or mitigation measures.

In the SPS, electron clouds have been a major concern as soon as an LHC-like beam has been injected [16]. They trigger vacuum pressure rises, instabilities, beam losses and transverse emittance blow-up. Cures and mitigation measures have been developed through modelling/simulation and experimental tests. Scrubbing by the beam for LHC is showing an interesting potential, as demonstrated by the continuous improvement of the SPS since the beginning of operation for LHC. It suffers however from degradation whenever the vacuum chambers are exposed to atmosphere and the minimum obtainable Secondary Electron Yield (SEY) is limited, depending upon the nature and cleanliness of the vacuum chamber. Coating of the vacuum chamber with a low SEY material would be a perfect cure, completely avoiding the appearance of electron clouds. Amorphous carbon is especially efficient in that respect and adequate coating processes for the SPS vacuum chambers have been developed and experimentally demonstrated. The use of clearing electrodes has also been considered, but no satisfying engineering solution has been found which would not reduce the available aperture. In any case, getting rid of the electron cloud limitations in the SPS is considered as

feasible, either with scrubbing or with amorphous carbon coating [17]. As a mitigation measure, a wideband (GHz bandwidth) transverse damper is also envisaged as a possible means to counteract electron cloud triggered instabilities [18].

3.4 Other upgrades

The equipment in all accelerators must match the increased level of performance and be capable to operate reliably:

- New beam instrumentation has to be developed for measuring with adequate accuracy beams of reduced size and high brightness and intensity. The capability to detect and quantify the intensity in "spurious" bunches in the PS and in the SPS is an important and challenging need.

- New beam intercepting and protection devices have to be built which withstand impact from the higher brightness / higher intensity beam. That concerns beam dumps in all machines, as well as the SPS scraper system for halo shaping and the devices in the SPS to LHC transfer lines protecting the LHC.

- A number of power supplies need to be replaced because of aging and/or because of more demanding specifications.
- Civil engineering and building construction are also necessary for radiation shielding (PS injection and ejection sectors) and to host new large size equipment (PSB new main power supply and new SPS high power RF amplifiers).

Very expensive items like the main dipoles are not planned to be changed, but their ageing will be carefully monitored and spares have to be available.

3.5 Beam characteristics after the upgrades

The performance reach of the LHC proton injector complex after the improvements described in the previous section are graphically represented in Fig. 5. Compared e.g. to the present situation with 25 ns (Fig. 3), the intensity per bunch doubles and brightness is $\sim 60\%$ larger.

The baseline option preferred by the LHC experiments is 25 ns bunch spacing. It is also preferable for the injectors because the beam characteristics expected by the HL-LHC project (red dot) are approximately compatible with all identified limitations, except with a space charge tune spread limit of 0.26 in the PS. The implementation in the PS of additional gymnastics of the kind described in section 2b) and in reference [7] or the success in the measures allowing a higher ΔQ or a combination of both are obvious paths for ultimately reaching the HL-LHC goal.

As a spare solution, in case the 25 ns beam cannot be used in the LHC (e.g. because of electron cloud or beam intensity), 50 ns bunch spacing could be considered. More limitations would then have to be faced in the injectors:

- in the PS, mainly because of longitudinal instability, with an estimated limit is $2.7 \cdot 10^{11}$ p/bunch, while the HL-LHC specification is at $3.5 \cdot 10^{11}$ p/bunch.
- in the SPS, because of longitudinal instability and because of space charge (the tune spread will reach 0.22 on the injection flat porch).



Fig. 5: Performance and limitations at SPS ejection of the upgraded LHC proton injector complex for 25 ns (left) and 50 ns (right) bunch spacing.

The performances shown in Fig.5 are however only estimates which will have to be regularly revised during the ~ 10 years duration of the injectors' upgrade programme. As past experience with the CERN accelerators has shown, it is not unreasonable to hope that, as a result of the intense effort invested both in theory and in beam experiments [19], beam characteristics will finally exceed the present expectation and meet the present HL-LHC requirements. Similarly, the possibility cannot be discarded that the HL-LHC beam specifications will evolve as experience with the collider progresses.

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