

LIU: WHICH BEAMS IN THE INJECTORS FULFILL HL-LHC UPGRADE SCENARIO 1 GOALS?

S. Gilardoni, G. Arduini, W. Bartmann, H. Bartosik, O. Bruning, H. Damerau, R. Garoby, B. Goddard, S. Hancock, K. Hanke, G. Iadarola, M. Meddahi, B. Mikulec, G. Rumolo, E. Shaposhnikova, G. Sterbini, R. Wasef, CERN, Geneva, Switzerland

Abstract

This paper summarizes the current understanding of the issues to be addressed in the injectors in order to fulfill the requirements of the HL-LHC in the framework of the upgrade scenario 1. The required beam parameters in the different accelerators are outlined, and the relevant performance limitations described. Possible beam production schemes are presented, and their relative merits are compared. The upgrades required in the preferred scenario are described and the beam characteristics potentially accessible at LHC injection estimated.

INTRODUCTION

The Upgrade Scenario 1, or US1, is considered as an intermediate possible scenario between realizing a minimum upgrade of the injectors, where only the consolidation would take place plus some performance increase thanks to the modification of the minimum requirements of the renovated hardware (Performance Improving Consolidation - PICS [1]), and the case in which a full upgrade (US2) is accomplished as proposed in [2].

DEFINITION OF UPGRADE SCENARIO 1

HL-LHC defined US1 according to Table 1, with the goal of reaching at least a total integrated luminosity of 2000 fb^{-1} , starting from an already cumulated luminosity of 300 fb^{-1} , and running for 160 days per year. The emittances quoted in Table 1 are given at the start of collisions in LHC. As reported later, a 20% emittance blow up and 5% losses should be used to extrapolate back to the beam parameters at injection, i.e., at SPS extraction.

The interventions or the areas of intervention required by the injectors to approach these parameters are listed in Table 2 and described in detail in the following sections. A special point has to be mentioned for the SPS 200 MHz RF system situation. Originally the full power upgrade of the system, as described in [3], was not included in US1, where only the low-level RF upgrade was considered. Eventually, it became clear that the preferred parameters for HL-LHC are not exclusively the ones mentioned in Table 1, in particular concerning the beam intensity. It is more interesting to exceed the intensity per bunch of 1.5×10^{11} at the expenses of the transverse emittances [6]. For this reason the 200 MHz RF system upgrade has to be included in US1, rendering US1 basically equal to US2 for the part concerning the injectors.

BEAM PARAMETER ESTIMATION

The expected beam performances reachable by implementing only the US1 options were determined under the following assumptions: all upgrades proposed for the injectors should be implemented (see Table 2) and commissioned, as Linac4 should deliver the nominal beam according to the brightness curve presented in [4].

The SPS, as already mentioned, is considered as a special case. The power upgrade of the 200 MHz was not originally included in US1, however it became immediately clear in the US1 performance analysis that this choice would create an intensity limit not compatible with the HL-LHC needs. For this reason, the distinction between US1 and US2 for the injectors, as presented in [2], becomes minimal. It is also assumed that electron cloud will not limit anymore the SPS performances, possibly thanks to the aC coating of vacuum chambers or new scrubbing techniques, or a combination of both [2].

For the preservation of beam quality in the injector complex, i.e., to respect the allocated budgets in terms of losses and emittance blow-up and to reproduce the same performances in terms of beam transmission realized with the 50 and 25 ns beams during Run 1 [4], the following assumption are used:

- the maximum Laslett tune shift due to direct space-charge in the PS should be limited to $|\mathbf{0.31}|$;
- the maximum Laslett tune shift due to direct space-charge in the SPS should be limited to $|\mathbf{0.21}|$;
- the maximum intensity per bunch deliverable by the SPS at extraction *with exclusively the 200 MHz LLRF upgrade* is **$1.45 \times 10^{11} \text{ p/b}$** [3];
- the maximum intensity per bunch deliverable by the SPS at extraction *with the 200 MHz LLRF and power upgrade* is **$2 \times 10^{11} \text{ p/b}$** [3].

The losses and emittance blow-up budgets are assumed per each machine according to Table 3. Losses and blow-up in the transfer lines should be considered as already included in the limits mentioned. For the LHC, the values refer to the difference between the beam at injection and in collision. Only the 25 ns bunch spacing is considered in this analysis.

Following all these considerations, Table 4 summarizes the beam parameters as requested by the LHC and offered by LIU for the different upgrade scenarios and beam production schemes described in the next section. The scenario

Table 1: Upgrade Scenario 1 as originally defined. Intensity per bunch and emittances are considered in collision

LHC performance	Overall Phys. Op. [years]	I_b [10^{11}]	β^* [m]	ϵ^* [$1\sigma \mu\text{m}$]	$\int \mathcal{L}/y$ [fb$^{-1}$]	$\int \mathcal{L}$ over 10 y [fb$^{-1}$]	Total $\int \mathcal{L}$ [fb$^{-1}$]
Baseline US1	10	1.5	0.15	1.5	170	1700	2000
Alternative US1	10	1.2	0.15	1	170	1700	2000

Table 2: Upgrade Scenario 1 as defined in the injectors. The activities specific to US1 are indicated in *italic*, whereas the others activities are already at least partially included in PICS [1]

PSB	PS	SPS
Main and auxiliary Magnets	Beam Instrumentation	Machine interlocks
LL RF	Auxiliary Magnets	800 MHz upgrade
HL RF	Transverse damper	Improved vacuum sectorisation LSS1
Power converters L4 injection	Longitudinal damper	Scraper improvement
Power converters ring, extraction and TL	Radiation shielding	Beam Instrumentation
Beam instrumentation	Power converters	Transverse damper
Beam intercepting devices	Beam dumps	Improved vacuum sectorisation arcs
Linac4 injection	<i>2 GeV injection</i>	New TIDVG core
<i>2 GeV extraction and transfer</i>	RF	Other kicker impedance reduction
Vacuum		200 MHz low level improvement
Electrical Systems		<i>200 MHz power upgrade</i>
Cooling and Ventilation		SPS and TI2/TI8 protection devices
Installation, Transport and Handling		
Civil Engineering		
Interlock Systems		
Control		

mentioned as *Extended* implies that the LHC would be ready to accept any beam from the injectors in which the intensity per bunch will be larger than $1.45e11$ and produced in emittances larger than $1.8 \mu\text{m}$ (1σ norm.). A more de-

Table 3: Allocated budgets for transverse emittance increase and beam losses

Accelerator	$\Delta\epsilon/\epsilon$ %	Losses %
LHC	20	5
SPS	10	10
PS	5	5
PSB	5	5

tailed evaluation of the impact of the proposed LIU beam parameters for US1 can be found in [6], but it is already apparent that the LIU US1 scenario well fulfills the needs of the HL-LHC US1 requirements.

25 ns beam production schemes

The production of the 25 ns bunch spacing beam, which remains the baseline for the upgrade, is realized as follows. Linac2, or Linac4 in the future, fills each of the 4 PSB rings at 50 MeV (kinetic energy, 160 MeV for Linac4) on $h = 1$ (more precisely, each bunch is produced by filling a $h=1+2$ bucket). Each PSB bunch, in total 4, is transferred to the

PS on $h = 7$ and after 1.2 s, the PS receives two other PSB bunches. On the 1.4 GeV (kinetic E, 2 GeV in the future) PS injection flat bottom, the 6 bunches are captured. Then, after a first acceleration to 2.5 GeV, they are triple split. The resulting 18 bunches are accelerated up to 26 GeV/c where two consecutive double splittings produce the final bunch spacing of 25 ns creating a batch of 72 bunches. Prior to the transfer to the SPS, the bunches are rotated in the longitudinal plane to reduce the bunch length to about 4 ns. Up to four consecutive batches of 72 bunches are then injected in the SPS at 26 GeV/c, and accelerated to 450 GeV/c prior to extraction to the LHC. The longitudinal emittance is increased in the PS and SPS to reduce longitudinal instabilities, whereas transverse scraping is done in the SPS before reaching the extraction energy to eliminate tails. Beside the classical production scheme, alternative ones were proposed to overcome the brightness limitation of the PSB. The most promising one named BCMS (Batch Compression Merging and Splittings), comprises the injection of 2×4 bunches on the 9th harmonic in the PS, batch compression from $h=9$ to $h=14$, bunch merging followed by a triple splitting all done at low energy instead of the triple splitting only. These evolved RF gymnastics are performed at an intermediate kinetic energy ($E_k = 2.5$ GeV) to avoid transverse emittance blow up due to space charge and to relax the requirements on the longitudinal emittance at injection. The resulting 12 bunches are accelerated to the extraction

Table 4: LHC requirements vs. injector performances after US1. The transverse emittances are the average of the two transverse planes.

Scenario	I_b [10^{11}]	ϵ^* [$1\sigma \mu\text{m}$]	Evaluation point
US1 requirements (LHC collision/injection Baseline)	1.5/1.58	1.5/1.25	in LHC
US1 requirements (LHC collision/injection Alternate)	1.2/1.26	1/0.83	in LHC
US1 <i>Extended requirements (LHC collision/injection)</i>	> 1.45	> 1.8	in LHC
Linac4 + 2 GeV + SPS LLRF upgrade US1 (PS Standard scheme – 72 bchs)	1.45	1.37	at SPS extr.
Linac4 + 2 GeV + full SPS upgrade (PS Standard scheme – 72 bchs)	2.0	1.88	at SPS extr.
Linac4 + 2 GeV + SPS LLRF upgrade (PS BCMS scheme – 48 bchs)	1.45	0.91	at SPS extr.
Linac4 + 2 GeV + full SPS upgrade (PS BCMS scheme – 48 bchs)	2.0	1.37	at SPS extr.

flat top where two bunch splittings occur to obtain the final 25 ns bunch spacing (only one splitting is done for the 50 ns bunch spacing) as for the nominal scheme. The advantage with respect to the traditional scheme results from the smaller splitting factor of the PSB bunches (6 instead of 12). Before extraction to the SPS, 25 ns spaced bunches have the same transverse emittance but twice the intensity. Beams will be produced according to this scheme for the LHC Run 2.

Challenges of traditional schemes and proposed solutions

The double injection in the PS needed to maximize the number of bunches after the longitudinal splitting requires also very high intensity injected in the PSB. Every PSB bunch is split up to 12 times to get finally 72 bunches at 25 ns spacing at PS extraction, but fewer times for BCMS. This requires Linac2 to inject a high intensity beam with a limited brilliance, due to the multi-turn injection process and large space-charge (see [4]). This issue will be solved with the connection of Linac4, which will bring the injection energy from 50 MeV to 160 MeV, a clear advantage for space charge limitations, but also will use H^- instead of protons, making the transverse painting more effective. It is expected that the brilliance of the PSB could be doubled thanks to the new linac [4].

Once the first batch is injected from the PSB to the PS, there is a 1.2 s long waiting time on the PS flat bottom before the second injection can be delivered. During this period, the beam has a very large tune spread induced by the direct space charge, while the synchrotron period is of the order of 1 ms and very large chromaticity in absolute value. The beam, due to the synchrotron motion, crosses many times the integer and the $4q_v=1$ resonance, creating transverse emittance increase and beam losses. The most robust solution to avoid this limitation is, for the fourth time in the PS history, to increase the injection energy, this time from 1.4 GeV to 2 GeV [5]. The reduction of direct space charge effect thanks to the energy increase leaves just enough space in the tune diagram to accommodate the tune shift expected for the future HL-LHC type beams.

Once the triple split beam is accelerated, right after transi-

tion crossing, coupled bunch longitudinal instabilities are observed. The consequences are beam losses and a significant variation of longitudinal emittance and intensity along the extracted batch. This lack of reproducibility is a major source of losses, in particular capture losses, in the SPS. The preferred solution for this limitation is the use of a longitudinal damper, a function provided by a newly installed Finemet® cavity. Electron cloud is regularly observed on the extraction flat top, even if there is no evident sign that the beam quality is affected. There is instead a clear horizontal instability appearing, together with electron cloud, if the bunches are shorter than nominal or if the beam is kept artificially in the machine 50 ms longer than necessary. In case this becomes a limitation for the future beams, it was shown that the transverse damper can effectively delay the instability by about 10 ms.

The limitations in the SPS come again from the long waiting time at flat bottom due to the multiple injections (up to 5 from the PS), and by the lack of RF power during acceleration and at flat top. An upgrade of the 200 MHz RF system is then proposed, and it turned out to be necessarily part of US1 for the injectors to be able to fulfill the intensity needs of the LHC. Another major limitation of the SPS could be caused by electron cloud effects resulting in pressure rise, beam instabilities, emittance growth and losses. As presented in more detail in [2], it is commonly accepted that either scrubbing, or coating with aC all or a part of the vacuum chambers, or a combination of both will solve the electron cloud issue after LS2.

Summary of US1-PSB

The two main upgrades of the PSB concern the injection and extraction processes. At injection, Linac2 will be replaced by Linac4, with a more modern H^- injection at 160 MeV instead of the old-fashioned proton injection at 50 MeV. This will permit the doubling of the beam brightness.

The new Linac4 requires the complete exchange of the injection elements: a new painting scheme (in 4 or 6 dimensions) with charge-exchange will replace the proton injection with transverse painting. The injection region design shows already that the integration of the different devices is clearly challenging.

Table 5: Upgrade Scenario 1

	2 GeV-w/o 200 MHz	2 GeV-with 200 MHz	Implication if not done
Linac4 connection	Commissioning of Linac and PSB injection		Space charge limit in PSB
PSB to PS at 2 GeV	Commissioning of extraction-injection devices		Space charge limit in PS
Longer bunches for PSB to PS	To be tested to assess full gain		Space charge limit in PS
PS T-damper for Headtail	Low risk, Headtail as today with ξ_x control		Losses
PS Transition crossing	Stable beam expected	More studies needed	Large losses
e-cloud PS	T-Damper can be used. BCMS should be better		Emittance blow-up
SPS Space charge	The PS limit is reached before the SPS		
SPS 200 MHz upgrade	Max. intensity 1.45e11 p/b	Max. intensity 2e11 p/b	
e-cloud in SPS	Assumed as solved. BCMS should be better		Losses/emittance blow-up

The new extraction energy will bring the main magnets very close to their maximum capabilities, whereas many of the auxiliary systems will need to be replaced. A new POPS-like main power supply will replace the existing one. Concerning the extraction elements in the ring, a series of tests will confirm which ones are not suitable for the new operation, whereas the recombination kickers will be replaced. The PSB-PS transfer line will become PPM and all the principal magnets will be replaced, with the possibility of operating different optics for LHC and fixed-target beams. The PSB external dump will be replaced to cope with the future high-power beams.

Summary of US1-PS

The increase of the injection energy to 2 GeV is needed to reduce space-charge-induced transverse emittance blow-up experienced by the first batch injected on the flat bottom. The new 2 GeV injection requires new injection elements and power converters, (septum, kicker, injection bumpers). In addition to that, new magnets and power converters for orbit correctors and lattice quadrupoles used at low energy will also be produced to cope with the higher injection energy. Unlike the PSB, there is no need for a new MPS. Headtail instabilities on the injection flat bottom, which are currently cured by introducing linear coupling, will also be controlled thanks to the power upgrade of the transverse damper together with the chromaticity control needed to avoid high order modes.

A fast vertical instability, which was extensively studied on single bunch beams, was observed also on a special high-intensity single-bunch LHC-type beam. Even if the future HL-LHC beams should be stable at transition, future studies with small longitudinal emittance beams will be done to confirm the extrapolation from past measurements.

As mentioned, the longitudinal coupled bunch instability, if not cured, would limit the maximum intensity per bunch well below the 2.5e11 p/b of the future HL-LHC type beam. A new dedicated longitudinal damper, based on a Finemet© cavity and a new LL-RF system is being installed during LS1.

As mentioned e-cloud is observed during the 25 ns beam production but with no influence on beam quality, so this is not expected to be an issue in the future. In any case, stud-

ies carried out during the 2012-2013 run [7], proved that the transverse damper can effectively delay the appearance of the instability. In an alternative scheme, a faster final phase rotation may also be used. If e-cloud would turn out, even after all the countermeasures deployed, to be a limitation, beam production schemes with reduced number of bunches, 48 for example, might be used instead. This of course would cause a minor reduction of the number of bunches in the LHC [8], but would still make it possible to approach the HL-LHC requirements.

Summary of US1-SPS

Amongst the different systems requiring an upgrade [2] to cope with the intensity increase for the HL-LHC, the RF system is the most affected by major changes. The beam intensity in the SPS is presently limited by longitudinal instabilities on the ramp and at flat bottom in combination with beam loading in the travelling wave cavities. During acceleration, done with the 200 MHz system alone, the beam becomes longitudinally unstable for an intensity of about $2\text{--}3 \cdot 10^{10}$ ppb for the 25 ns bunch spacing. Presently this is mitigated by the 800 MHz RF system operating in bunch-shortening mode and a significant controlled longitudinal emittance blow up from 0.35 eVs to 0.5 eVs done with the 200 MHz system [9]. The solution proposed to overcome this limitation is the upgrade of the 200 MHz system, with an increase of the available RF power by at least factor of 2 obtained by increasing the number of cavity modules and by rearranging sections to reduce the impedance by about 20% [9]. As an intermediate step, in principle, it should be possible to operate the RF in pulsed mode (after consolidation) to increase the available power seen by the beam. This operation was never tested with high intensity beams and needs a completely new low-level RF, and it arises some concerns for the reliability of the system. By doing so, the total available power at extraction would be 1.05 MW, and it will probably be possible to reach 1.45e11 ppb with no performance degradation of the extracted beam. In case the full upgrade of the 200 MHz system would take place, as preferred for the US1 case, the maximum available power for 2 longest (4 sections) cavities would be instead about 1.6 MW, bringing the maximum intensity per bunch up to 2.0e11 for 25 ns without

any performance degradation in the hypothesis that no new beam stabilities with high intensity (combination of single- and coupled-bunch effects) would appear in the new working regime. Concerning the other SPS activities, a more detailed discussion can be found in [2] for US2.

Risk analysis

A very simplified risk analysis was done considering the implementation of the new elements in the different machines and the results are summarized in Table 5. The two different columns refer to the case with or without the 200 MHz upgrade implementation in the SPS. The activity mentioned concerns only the main group of interventions/limits.

CONCLUSIONS

The HL-LHC US1 requirements can be fulfilled if the three main injector upgrades foreseen by LIU are implemented, i.e., the connection of Linac4, the PSB extraction energy upgrade to 2 GeV and SPS 200 MHz RF power upgrade. In particular the 200 MHz power upgrade is necessary to match the requirements of the preferred HL-LHC-US1 scenario with unchanged parameters at LHC injection (longitudinal in particular).

REFERENCES

- [1] K. Hanke *et al.*, these proceedings
- [2] H. Bartosik *et al.*, these proceedings
- [3] E. Shaposhnikova, LIU technical meeting
<http://indico.cern.ch/event/262482/>
- [4] G. Rumolo *et al.*, these proceedings
- [5] M. Giovannozzi *et al.*, Chamonix 2010
- [6] O. Brunning *et al.*, these proceedings
- [7] G. Sterbini, CERN-ACC-2013-0215
- [8] H. Damerau *et al.*, these proceedings
- [9] E. Shaposhnikova *et al.*, WE01A04, HB2012.