THE HIGH INTENSITY/HIGH BRIGHTNESS UPGRADE PROGRAM AT CERN: STATUS AND CHALLENGES

S.S. Gilardoni, G. Arduini, T. Argyropoulos, S. Aumon, H. Bartosik, E. Benedetto, N. Biancacci, T. Bohl, J. Borburgh, C. Carli, F. Caspers, H. Damerau, V. Forte, R. Garoby, M. Giovannozzi, B. Goddard, S. Hancock, K. Hanke, A. Huschauer, G. Iadarola, M. Meddahi, G. Métral, E. Métral, B. Mikulec, J.E. Muller, Y. Papaphilippou, S. Persichelli, G. Rumolo, B. Salvant, F. Schmidt, E. Shaposhnikova, R. Steerenberg, G. Sterbini, M. Taborelli, H. Timko, M. Vretenar, R. Wasef, C. Y. Vallgren, C. Zannini, CERN, Geneva, Switzerland
G. Franchetti, GSI, Darmstadt, Germany
A.Y. Molodozhentsev, J-PARC, KEK & JAEA, Ibaraki-ken, Japan
V. Vaccaro, Naples University Federico II, Napoli, Italy
M. Pivi, SLAC, Menlo Park, California, USA
M. Migliorati, University of Rome La Sapienza, Rome, Italy

Abstract

The future beam brightness and intensities required by the HL-LHC (High-Luminosity LHC) project and for possible new neutrino production beams triggered a deep revision of the LHC injector performances. The analysis, progressing in the framework of the LHC Injectors Upgrade (LIU) project, outlined major limitations mainly related to collective effects - space charge in PSB and PS, electron cloud driven and TMCI instabilities in the SPS, longitudinal coupled bunch instabilities in the PS for example - but also to the existing hardware capability to cope with beam instabilities and losses. A summary of the observations and simulation studies carried out so far, as well as the future ones, will be presented. The solution proposed to overcome the different limitations and the plans for their implementation will be also briefly reviewed.

INTRODUCTION

The LHC upgrade foreseen for the high-luminosity run, planned after 2020, requires a vigorous upgrade for the injectors that will be realized in the framework of the LHC Injectors Upgrade (LIU) project. The new beam requirements, presented in Table 1 [1, 2], imply an increase of the beam brightness delivered by the injectors by about a factor of two. This could be realized only thanks to a series of major changes in all the machines of the injector complex plus the introduction of the new Linac4. In the following sections the main challenges related to the production of the high-brilliance 25 ns bunch spacing LHC beam are presented. The details on the hardware changes foreseen for the different machines can be found in [3] and in the references therein. The last section of this paper deals with new requirements for proton beams arising from the new proposals of short and long baseline neutrino experiments, requesting a beam power from the SPS up to 750 kW.

25 ns Bunch Spacing Production Schemes

The production of the 25 ns bunch spacing beam, which remains the baseline for the upgrade, is realized as follows. The Linac2 fills each of the 4 PSB rings at 50 MeV (kinetic E) on $h = 1$. 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) PS injection flat bottom, the 6 bunches are triple split. The resulting 18 bunches are accelerated up to 26 GeV/c where two consecutive longitudinal 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 [4, 5]. 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.

Different challenges are related to the aforementioned production scheme. The first limitation is due to the high intensity injected in PSB, since every PSB bunch is split in the PS 12 times to obtain finally 72 bunches. Clearly, space-charge induced transverse blow up might spoil the small emittance delivered by the Linac during the injection process [6]. The second limitation is produced by the existing PSB injection process based on transverse painting, resulting in a linear correlation between transverse emittances and beam intensities (constant brightness). Both issues should be overcome with the Linac4, that will deliver 160 MeV (kinetic E) H^- to the PSB instead of protons at 50 MeV. The third limitation is due to the long waiting time of the first batch of 4 bunches on the PS injection flat bottom: the large vertical space-charge tune shift of the order today of -0.28 and in the future required to be as high as -0.34 might cause transverse emittance blow up due to resonance crossing. The reduction of the space-charge tune shift to more acceptable values will be realised thanks to the increase of the extraction energy from the PSB from

ISBN 978-3-95450-118-2

Table 1: LHC-beam (Operational Data Summer 2012) vs. HL-LHC Requirements for Two Different Bunch Spacings

Parameters at LHC collision	**Nom. 25 ns**	**2012 50 ns**	**HL-LHC 25 ns**	**HL-LHC 50 ns**
Int./bunch [10^{11}]	1.15	≈ 1.6	2.2	3.5
Bunches	2808	1374	2808	1404
Current [A]	0.58	0.39	1.11	0.88
$\epsilon^*(1\sigma)$ [μm]	3.75	≈ 2.4	2.5	3.0
β^* [m]	0.55	0.6	0.15	0.15
L_{peak} [10^{34} cm^{-2}s^{-1}]	1	0.77	24	25

1.4 GeV to 2 GeV [7]. This implies a major upgrade of the PSB, in particular of the main magnet power converter, as for the PSB-PS transfer elements. Last, in the PS head tail instabilities have been observed already in the past at low energy, today cured by the introduction of linear coupling [8].

Similar limitations in the transverse plane appear also on the long SPS injection flat bottom: the first of the four batches injected from the PS is kept for about 10.8 s before acceleration. Space-charge could be the cause of transverse emittance blow-up, but also TMCI (Transverse Mode Coupling Instability) is known to constitute one of the hard-limiting factor already for single bunch stability. The latter could be recently cured by the introduction of a new optics, as described below and in [9].

Many RF systems are involved in the different injectors for the 25 ns beam production: In the PSB, the three obsolete RF systems will be most probably replaced by a single more modern wide-band one based on Finemet® technology; in the PS coupled bunch instabilities and transient beam loading will be cured by a new dedicated longitudinal kicker plus new feedbacks; in the SPS a major upgrade of the two RF systems, as described later and in [10], will overcome the intensity limitation due to the lack of available voltage.

In parallel with the improvements required to cope with the classical generation scheme for the 25 ns beam, new ones based on batch compression and bunch merging are under investigation [11]. The goal of these studies is to try to improve the beam brightness before the connection of the Linac4 and energy increase of the PSB. The most promising one includes double batch injection of 4 bunches from the PSB in the PS on the harmonics 9 profiting from the full brightness of all four PSB rings for both injections. The 8 bunches are accelerated to 2.5 GeV where they are compressed with an harmonics sweep $h = 9, 10, 11, 12, 13, 14$ followed by a bunch merging from $h = 14$ to $h = 7$. The 4 bunches are then triple split, accelerated to 26 GeV/c and finally double split again twice to obtain 48 bunches spaced by 25 ns. First tests were carried out during the summer of 2012. A 50 ns beam, with then 24 bunches, was produced and successfully injected and accelerated in the SPS.

Proposed Upgrade Timeline

The planning for the injector upgrade is obviously determined by the LHC operation, but also by the beam availability to the non-LHC experiments. As currently proposed, the upgrade timeline should be the following:

- Q1 2013: Analysis of different limitations and parameter definition together with HL-LHC. LIU Project Baseline definition;
- 2013 - Q2 2014: Long shutdown 1. Limited hardware interventions for the injectors. Resources focused on LHC splice renovation;
- Q2 2014 - 2018: Normal operation period, starting with beam delivered only to the non-LHC experiments until the end of the LHC shutdown;
- Q4 2015: Linac4 commissioning finished. PSB H^- injection available;
- 2018 - 2019: Long shutdown 2. Resources focussed on LIU related activities;
- 2019 and beyond: PSB-PS transfer ready at 2 GeV. SPS amorphous Carbon (aC) coating done, 200 MHz power upgrade completed. Injector commissioning for the upgraded LHC beams.

DETAILED UPGRADE PLAN

The upgrade of the beams, in terms of higher intensity, smaller transverse emittances, better quality, can be realised thanks to a profound revision of the different machine limitations and important interventions beyond a simple consolidation of the existing infrastructures. One should not forget, in fact, that in 2012 the PSB is 40 years, the PS 53 years and the SPS 36 years old. The upgrade starts with the introduction of the new H^- linac, the Linac4, replacing the Linac2, and continues with a vigorous modernization of all downstream accelerators.

Linac4

The detailed status of the Linac4 and its commissioning are discussed in [12]. The installation of the new infrastructure (electricity, cooling, ventilation, racks, cabling,

ISBN 978-3-95450-118-2

RF Network) should be completed in autumn 2012, following the finishing of the construction of the linac buildings. In the meanwhile, the 3 MeV injector, which includes the Ion source, the LEBT, the RFQ and MEBT line, is being installed in a dedicated test stand to start the beam commissioning as soon as possible. At the same moment, the accelerating structures are being assembled or delivered at CERN and after RF testing will be installed in the tunnel from end of 2013. The commissioning in the linac tunnel should take place from the middle of 2013, limited to the 3 MeV line, followed then by DTL in the first half of 2014, the CCDTL in second half of 2014, with the PIMS tests starting in the early part of 2015. Even if the Linac4 could be ready to deliver beam to the PSB most probably by the end of 2015, the connection to the complex will take place only during the next long LHC shutdown in 2018, preceded by a series of beam tests and improvements of reliability. The connection will require an interruption of the proton production at CERN longer than six months, too long to be included in a normal winter shutdown.

PSB

As mentioned in the introduction, the main limitation for the production of the LHC-type beams in the PSB is related to the injection at 50 MeV from the Linac2, currently based on transverse painting. This technique results in a linear correlation between transverse emittance and beam intensity, with the minimum emittance reachable being the one delivered by the Linac2. In this situation, numerous studies reported in [13] were done to assess the maximum Laslett tune shift acceptable for the LHC-type beams. Different beam intensities are delivered by the linac and the Laslett tune shift is evaluated at different energies in the cycles for a specific bunching factor obtained by modulating the relative phase and voltage of the two main RF systems. As example, a LHC-type beam with a final bunch spacing of 25 ns would require from a PSB ring an intensity of about 160 10^{10} p (including loss budget), corresponding to a tune shift well above the -0.5. Currently, the PSB can operate with a tune shift of that order without a noticeable degradation of the beam quality. It is of primary importance to improve the understanding of transverse emittance behavior with large space charge tune shift and eventually improve resonance compensation used today in normal operation and propose one for 160 MeV operation. The introduction of the Linac4 will eventually results in beams with unprecedent brightness, thanks to the higher injection energy and the use of H^-, but the full exploitation of the Linac4 capability will be possible only once the limitations of the other machines will be overcome. Of particular concern for example is the compensation of the beta-beating introduced by the edge focusing of the new bumpers used during the H^- injection as reported in [6].

PS

The PS limitations for the LHC beam production are somehow wider than for the PSB. On the injection flat bottom space charge and head tail instabilities could spoil the precious and tiny transverse emittance. During acceleration, longitudinal coupled bunch instabilities (CBI) degrade the longitudinal beam quality in terms of bunch-to-bunch intensity and emittance spread and transient beam loading can spoil the longitudinal emittance. On the extraction flat top, again longitudinal CBI and transverse instabilities could degrade the beam just prior to extraction. The space charge issue will be alleviated by the increase of the injection energy to 2 GeV. The experience acquired with the LHC operational beam, in particular the 50 ns bunch spacing currently delivered for physics to the LHC, proved that the transverse beam quality is conserved even with vertical Laslett tune shift of the order of about -0.28 at 1.4 GeV (maximum required by the upgrade is -0.34 at 2 GeV) for a vertical tune Q_y=0.23. The identification of other possible dangerous resonances than the integer has been done by scanning the tune phase space while recording beam losses [14]. Driving terms measurements were done with the goal of improving the PS magnetic model to determine, eventually, a resonance compensation scheme if needed. Skew and normal sextupolar resonances used to be compensated already in 1970s [15]. The scheme was then abandoned thanks to increase of the injection energy from the PSB. A large fraction of the experimental studies will be devoted to a better understanding of the effect of the integer resonance. It is clear that the edge of the space charge neck tie for current beam operation is at the limit of the stop band, and will probably be also in the future. A vigorous campaign of PTC-Orbit [6] simulations, using an effective machine model deduced from the fit of the non-linear chromaticities [16], has been launched as for the other machines to improve the understanding of the space charge limits. In this case, the lack of knowledge of the detailed measured magnetic errors imposed their evaluation based on Opera® simulations starting from construction tolerances. The results of the latter are then fed to the PTC-Orbit simulation, still under development. Concerning the other PS limitations in the transverse planes, the commissioning of a new transverse damper is coming to its conclusion. The new system proved to be able to damp: head tail instabilities, injection oscillations, high energy instabilities observed for bunches shorter than nominal. The source of this latter instability has not been identified, even if it is observed in correspondence of electron cloud formation but the correlation between the two could not be proved yet.

The PS radiofrequency systems are also going to be improved, in particular to reduce the effect of coupled bunch instabilities during acceleration and on the flat top. For this reason, new feedback loops will be installed on all the RF systems, plus a new longitudinal kicker based on the Finemet® technology will become available after 2013.

ISBN 978-3-95450-118-2

Table 2: Proton Beam Parameters for Neutrino Production Beams. The asterisks (*) indicates that feasibility including operational viability (especially in the PS) remains to be demonstrated

	Operation		SPS record		After LIU (2020)	
					Aim	Study
	LHC	CNGS	LHC	CNGS	LHC	post-CNGS
SPS beam energy [GeV]	450	400	450	400	450	400
Bunch spacing [ns]	50	5	25	5	25	5
Bunch intensity [10^{11}]	1.6	0.105	1.3	0.13	2.2	0.17
Number of bunches	144	4200	288	4200	288	4200
SPS beam intensity [10^{13}]	2.3	4.4	3.75	5.3	6.35	7.0(*)
PS beam intensity [10^{13}]	0.6	2.3	1.0	3.0	1.75	4.0(*)
PS cycle length [s]	3.6	1.2	3.6	1.2	3.6	1.2/2.4(*)
SPS cycle length [s]	21.6	6.0	21.6	6.0	21.6	6.0/7.2
PS momentum [GeV/c]	26	14	26	14	26	14
Average current [μA]	0.17	1.17	0.28	1.4	0.47	1.9/1.6
Power [kW]	77	470	125	565	211	747/622

SPS

Similar limitations already mentioned for the PSB and the PS also apply to the SPS. Four batches of maximum 72 bunches each are injected on the flat bottom, with the first batch waiting for acceleration for 10.8 s. Transverse emittance blow up due to space charge is of concern. On top of this, the single bunch intensity was limited until summer 2012 by TMCI instabilities. This could be overcome by a change of the machine optics. The intensity threshold of the TMCI instabilty is, in fact, proportional to the slip factor $\eta = 1/\gamma_{tr}^2 - 1/\gamma^2$, γ_{tr} being the relativistic gamma at transition energy and gamma the relativistic factor. Thanks to the optics change, described in [9], γ_{tr} could be shifted from 22.8 to 18 with the integer of the horizontal tune changed from 26 to 20 (hence the new optics name is Q20). The net result is an increase of the slip factor at injection by about a factor of 3, increasing the intensity instability threshold from 1.6 10^{11} p/b to more than 4 10^{11} p/b. The Q20 optics is going to be deployed soon in normal operation, as it provides also significant improvements for longitudinal stability, as well as electron cloud instability and a slightly smaller space charge tune spread due to the larger dispersion in the arcs. In fact, longitudinal instabilities in the SPS are of major concern for future high intensity LHC beams. A second concern for the SPS is coming from the RF systems, the 200 MHz and the 800 MHz. For present beam intensities, total particle losses in the SPS do not exceed 6%, but they increase for higher intensities. Losses are observed at injection from un-captured beam. A fraction of these are due to the mismatch between the bunch with thick tails resulting from final bunch rotation at PS extraction and the 200 MHz SPS bucket. A very detailed optimization of the PS bunch rotation, described in [17], is expected to lead a significant reduction of the capture losses. During acceleration, done with the 200 MHz system alone, the beam becomes longitudinally unstable for about 2-3 10^{10} 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 0.6 eVs done with the 200 MHz system [17]. Considering the upgrade beam parameters, the controlled blow up should be even further increased leading to potential increase of capture loss in the LHC. The solution proposed to overcome this limitation is the upgrade of the 200 MHz system, with 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% [10]. This renovation, which includes a beam control upgrade together with Q20 optics and upgrade of the 800 MHz RF system, should improve the beam stability to reach eventually 2.3 10^{11} p/b for 25 ns beams and more than 3.4 10^{11} p/b for the 50 ns required by HL-LHC.

Electron cloud driven instabilities could also constitute a limiting factor for the future beams, as in the past has been a major performance limit creating beam losses and emittance growth. Currently, the electron cloud is not a limitation for the production of the LHC beams, both with 50 ns and 25 ns bunch spacings, thanks to the conditioning accumulated over the years during dedicated 'scrubbing' periods. Unfortunately the recovery of the present performances after the exposition to air of a large part of the machine, for example during long shut down interventions, might require quite a long scrubbing period. Moreover it is not clear yet if a mitigation strategy based only on scrubbing will be sufficient to cope with future high brightness beams. For this reason, a robust solution developed with aC coating of the vacuum chambers inside the magnets is considered as upgrade baseline. In parallel with this, a high bandwidth transverse feedback system [18] is also under development, to help alleviating eventual transverse beam instabilities.

ISBN 978-3-95450-118-2

HIGH INTENSITY BEAMS UPGRADE

While recent upgrade studies are targeting the production of high brightness beams for the LHC, the production of eventually more intense proton beams required by new neutrino experiments is also under revision. The most demanding scenario [19] would require a beam power upgrade up to about 750 kW delivered by the SPS in regular operation. This program would thus imply a significant increase of the beam intensities delivered both by the SPS and the PS, whereas the intensity requested from the PSB seems to be already reachable with the foreseen upgrade. Table 2 summarizes the main parameters of the eventual future neutrino production beams compared to 2012 operation and the records achieved so far. The activities already foreseen for the injector upgrades will be for sure also beneficial for the neutrino production beams. In particular, thanks to the advent of the Linac4, it will be possible to inject much higher intensities in smaller transverse emittances. This should significantly contribute to overcome the current limitation in beam intensities, mainly due to the PS activation at injection but also in the SPS due to the limited aperture in the vertical plane. The high intensity beams in the SPS will profit from the upgrade of the 200 MHz and 800 MHz RF systems. Beams studies will concentrate on the use of the 800 MHz RF system to improve even further the beam stability. Transition crossing in the SPS is also a concern. Whereas the injection momentum of the LHC beams is 26 GeV/c, it is not possible to extract the neutrino production beams from the PS at a momentum higher than 14 GeV/c. This limitation is currently due to the maximum strength available of a elements used during the 5-turns [20] extraction. Even with the introduction of the new Multi-turn extraction (MTE) [21] from the PS this limitation will likely remain. The MTE extraction is based on beam trapping in stable islands: the beam is split in 5 beamlets by crossing of the fourth order resonances. The adiabaticity of the trapping process requires a long extraction flat top. If the transverse gymnastics would be realized at higher energy, a cycle 2.4 s long instead of 1.2 s used today would be needed, the duty cycle of the SPS will be considerably reduced, and hence the average beam power delivered to the target. The PS-SPS transfer is therefore limited to 14 GeV/c, that implies eventually a different optics compared to the Q20 used by the LHC beams. The last major intervention required in the SPS would be the installation of a new collimation system.

Concerning the PS, further studies for loss reduction all along the accelerating cycle will be needed, as well as a detailed analysis of the RF limitations in particular at transition crossing. It is also evident that the extraction used today, known as continuous transfer or CT, creates too large losses and ring activation even for today's intensity, and cannot be used for delivering the requested 4 10^{13} p/pulse on a regular basis. For this reason, the MTE extraction in normal operation is a prequisite for any intensity upgreade.

CONCLUSIONS

All the accelerators composing the LHC injector chain will be renovated to cope with the request of the HL-LHC and eventually to increase the maximum intensity deliverable for neutrino production. The commissioning of the high brightness beams is expected to start in 2019.

REFERENCES

[1] O. Brüning, F. Zimmermann, CERN-ATS-2012-070.

[2] B. Goddard et al., "Can the Proton Injectors meet the HL-LHC Requirements after LS2", Proceedings of the Chamonix 2012 LHC Performance Workshop.

[3] H. Damerau et al., CERN-ATS-2012-111.

[4] S. Gilardoni and D. Manglunki (eds.), CERN-2011-004.

[5] M. Benedikt et al. (eds.), CERN-2004-003-V-3.

[6] A. Molodozhentsev et al., WE01B05, these proceedings.

[7] M. Giovannozzi et al., "Possible improvements to the existing pre-injector complex in the framework of continued consolidation", Proceedings of the Chamonix 2010 LHC Performance Workshop.

[8] R. Cappi et al., CERN/PS 2001-010 (AE).

[9] H. Bartosik et al., WE01B01, these proceedings.

[10] E. Shaposhnikova et al., WE01A04, these proceedings.

[11] C. Carli et al. "Alternative/Complementary Possibilities", Proceedings of the Chamonix 2011 LHC Performance Workshop.

[12] J. B. Lallement et al., TU03B03, these proceedings.

[13] B. Mikulec et al., MOP249, these proceedings.

[14] S. Gilardoni et al., IPAC11, San Sebastian, Spain, 2011, MOPS014.

[15] Y. Baconnier, CERN/PS 87-89 (PSR).

[16] M. Giovannozzi et al., CERN-AB-2003-017-ABP.

[17] H. Timko et al., WE01C03, these proceedings.

[18] C. Rivetta, TH01B05, these proceedings.

[19] I. Efthymiopoulos, "Opportunities for ν-beams at CERN", Presented at Neutrino Town Meeting, CERN, 2012.

[20] J. Barranco and S. Gilardoni, CERN-AB-2008-021.

[21] M. Giovannozzi (ed.), CERN-2006-11.

ISBN 978-3-95450-118-2