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IMPROVED LONGITUDINAL PERFORMANCE OF THE LHC BEAM IN THE CERN PS

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Abstract

At the end of the 2018 run the intensity target for the High-Luminosity LHC (HL-LHC) had just been reached at extraction from the Proton Synchrotron (PS). In the framework of the LHC Injectors Upgrade (LIU) project additional RF improvements have been implemented during the 2019/2020 long shutdown (LS2), mainly impacting the impedance of the 10 MHz, 40 MHz, and 80 MHz RF systems. With the upgraded injection energy of 2 GeV (kinetic), also the intermediate plateau energy for RF manipulations has been increased. Following a campaign of beam studies throughout the 2021 run, a bunch intensity of up to $2.9 \cdot 10^{11}$ p/b in trains of 72 bunches is achieved with the required longitudinal beam quality, surpassing the LIU target of $2.6 \cdot 10^{11}$ p/b. The threshold of longitudinal quadrupolar coupled-bunch instabilities is increased during acceleration, but they are again observed at the flat-top. While dipolar coupled-bunch oscillations are well damped by a dedicated feedback system, the quadrupolar modes are suppressed by operating a 40 MHz system as an active higher-harmonic Landau cavity. The main commissioning steps are outlined, together with the key contributions to the improved beam performance.

INTRODUCTION

Doubling the bunch intensity of the beam from the Proton Synchrotron (PS) for the High-Luminosity LHC (HL-LHC) to $N_\mathrm{b} = 2.6 \cdot 10^{11}$ particles per bunch (p/b) at extraction, corresponding to a total beam intensity of $1.9 \cdot 10^{13}$ particles, has been a main objective of the LHC Injectors Upgrade (LIU) project [1]. To keep the bunch-by-bunch intensity spread acceptable for the LHC and to limit the beam loss at the PS-to-SPS transfer, the longitudinal beam quality has to be preserved at this increased intensity, i.e. 72-bunch batches (25 ns spacing) with a 4σ-bunch length below 4 ns and a longitudinal emittance below $\varepsilon_\mathrm{l} = 0.35$ eVs. Already since the first long shutdown (LS1) substantial upgrades of all RF systems in the PS have been implemented and commissioned. Their combined improvements allowed to reach the LIU intensity for the first time in 2018, although yet with very large transverse emittances. The upgrade programme was completed during the 2019/2020 long shutdown (LS2), mainly impacting the impedances of the 10 MHz, 40 MHz, and 80 MHz RF systems. The longitudinal beam production scheme has moreover been adapted to the increase of the injection energy from $E_\mathrm{kin} = 1.4$ GeV to 2 GeV, required to reduce space charge at flat-bottom for a higher transverse brightness [2]. Table 1 summarizes the main RF upgrades, focusing on changes during the LS2.

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Table 1: Renovations and Upgrades of RF and Feedback Systems During the LS2

RF system	Upgrade	Remark
10 MHz	• New wide-band feedback amplifiers	• $\simeq 4$ dB gain increase
	• 1-turn delay feedback, since 2014	• About 12 dB gain at $n \cdot f_\mathrm{rev}$
40 MHz 80 MHz	• Improved wide-band feedback systems	• Shorter delay by airlines
	• Multi-harmonic feedback systems	• Up to 26 dB gain at $n \cdot f_\mathrm{rev}$, new firmware
	• 40 MHz operation as Landau RF system at flat-top	
Wide-band	• Coupled-bunch feedback for dipole modes	• New firmware with internal diagnostics

CYCLE WITH INCREASED INJECTION ENERGY

The production scheme of the multi-bunch beams with 25 ns bunch spacing for the LHC is sketched in Fig. 1. The intermediate plateau, initially at $E_\mathrm{kin} = 2.5$ GeV, is needed to triple-split each bunch from the RF harmonic, $h = 7$ at injection to $h = 21$ during acceleration. The RF system would not provide a sufficiently large bucket area for the start of acceleration at $h = 21$ (9.5 MHz) otherwise. Additionally, for the higher-brightness variant of LHC-type beams [3] based on batch compression, merging and triple splitting (BCMS), the higher plateau energy reduces space charge during the RF manipulation. Following acceleration of 18 bunches through transition energy they are split in four by two consecutive splittings at the flat-top, increasing the principal RF harmonic via $h = 42$ (20 MHz) to $h = 84$ (40 MHz). Each bunch injected from the PSB is hence split in twelve parts in the PS. A non-adiabatic bunch rotation with RF systems at 40 MHz and 80 MHz shortens the bunches to fit them into the 5 ns long buckets in the SPS.

With the increased injection energy, the intermediate plateau would have been too close to the flat-bottom. The space charge tune shift is favorably reduced proportional to $1/(\beta\gamma^2)$ at higher energy, $\beta = v/c$ being the relative particle velocity, v, with respect to the speed of light, c,

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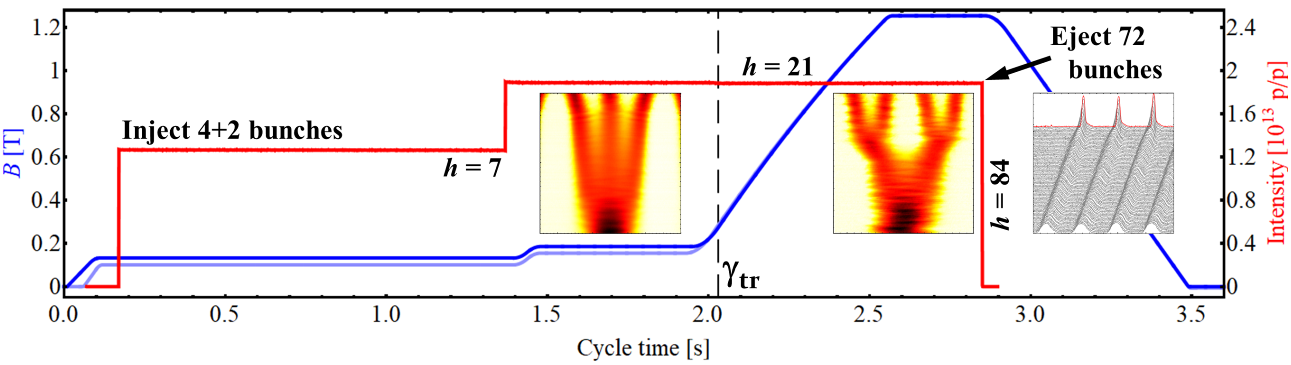

Figure 1: Cycle for the production of the nominal beam for the LHC with 25 ns bunch spacing. The bending field (blue) at flat-bottom and intermediate plateau has been adapted to E_{kin} = 2 GeV and injecton, compared to field evolution before LS2 with 1.4 GeV flat-bottom energy (light blue). The mountain range plots show a typical triple splitting (left), quadruple split (center) and the shortening prior to extraction (right). The measured total beam current (red) corresponds to a bunch intensity of $N_{\mathrm{b}} = 2.6 \cdot 10^{11}$ p/b.

and γ the Lorentz factor. However, while the bucket area for a given RF voltage increases with energy according to $A_{\mathrm{bucket}} \propto \sqrt{|\eta|/\gamma}$, the synchrotron frequency decreases inversely, $\omega_{\mathrm{S}} \propto \sqrt{\gamma/|\eta|}$. Well below the transition energy, γ_{tr}, the phase slip factor, $\eta = 1/\gamma_{\mathrm{tr}}^2 - 1/\gamma^2$, is approximately proportional to $1/\gamma^2$ ($\gamma_{\mathrm{tr}} = 6.1$ in the PS), and almost constant above. Additionally, the RF voltage during the triple splitting must be lowered to avoid the sensitivity to phase errors with shorter bunches, again decreasing the synchrotron frequency. Following adiabaticity studies, the new plateau energy has been fixed to an energy of E_{kin} = 3.1 GeV. Compared to its former energy of 2.5 GeV, the synchrotron frequency is halved when keeping the same initial bunch length for the splitting. The plateau duration then remains just sufficient for the complete BCMS manipulation without noticeably increasing uncontrolled emittance growth.

With the post-LS2 injection energy increase, the bucket area for the same RF voltage becomes about 1.5 times larger, allowing the PS to accept significantly larger longitudinal emittance than at E_{kin} = 1.4 GeV. A nominal longitudinal emittance of ε_{l} = 3 eVs per bunch lowers the maximum line density to reduce space charge at the flat-bottom. However, for the target emittance of 0.35 eVs (to be multiplied by $3 \cdot 2 \cdot 2 = 12$, due to the splitting ratio) the cycle only has 40% headroom for uncontrolled growth during the entire sequence of RF manipulations and transition crossing. This leaves little margin for any further reduction of the longitudinal emittance at PS extraction, which may be beneficial for the transfer to the SPS.

INTENSITY REACH

An extensive campaign of beam studies has been performed to push intensity and longitudinal beam quality of LHC-type beams in the PS towards the requirements for the HL-LHC. The evolution of the maximum bunch intensity at extraction in batches of 72 bunches is illustrated in Fig. 2. The coupled-bunch feedback with a wide-band cavity based on Finemet material as a longitudinal kicker [4,5] practically removed any dipole coupled-bunch oscillations during acceleration and at the arrival of the flat-top. To keep the relative RF phases under control during the splitting manipulations, 1-turn delay (10 MHz) or multi-harmonic feedback (40 MHz and 80 MHz) is applied in combination with direct feedback to reduce beam induced voltage [6,7].

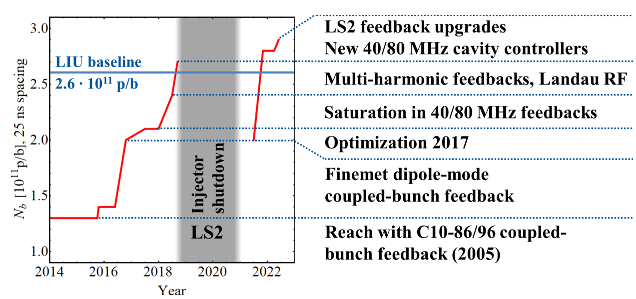

Figure 2: Maximum bunch intensity at PS extraction in batches of 72 bunches spaced by 25 ns.

While the LIU intensity had just been reached before LS2, the additional upgrades, mainly the exchange of the driver amplifiers in the direct feedback of the ten main 10 MHz accelerating cavities allowed to surpass $N_{\mathrm{b}} = 2.6 \cdot 10^{11}$ p/b with comfortable margin. Also the overall transmission, comparing the sum intensity (Fig. 2, red) of both injections with the intensity at extraction, is excellent with a total particle loss at the percent level.

LONGITUDINAL BEAM QUALITY

A small spread of bunch parameters, at the 10% level, in terms of intensity, bunch length and longitudinal emittance of the 72 bunches at extraction from the PS is essential for SPS and LHC. Longitudinal intensity effects in the form of coupled-bunch instabilities, transient beam loading and uncontrolled emittance growth lead either to unequal bunch splitting or large tails or both.

The signal processing of the present coupled-bunch feedback only covers all dipole oscillations, and the quadrupolar

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coupled-bunch oscillations growing at the flat-top (Fig. 3) remain undamped. These oscillations build up along the batch, resulting in emittance growth of the tail bunches at extraction.

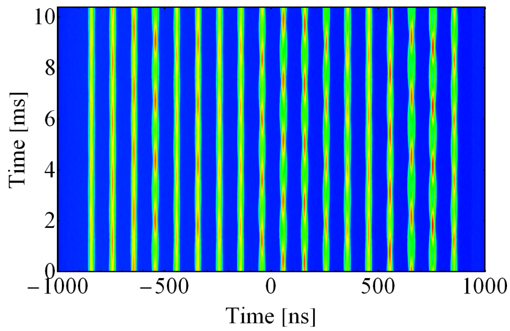

Figure 3: Quadrupolar coupled-bunch instabilities evolving at the flat-top (2021 data). The dominant mode number, $n = 4$ with a bunch-by-bunch phase advance of $\Delta\ \phi_{bb} = 4 \times 2\pi/18$, is identical to the one observed before LS2.

To stabilize the beam by increased Landau damping, a 40 MHz cavity is operated as a fourth-harmonic RF system [8]. Like in the SPS, this higher-harmonic RF system is in phase with respect to the fundamental one (bunch shortening mode) and fully suppresses the instability. Due to their small bandwidth the 40 MHz cavities can only be operated at and close to the flat-top. A novel signal processing for a quadrupolar coupled-bunch feedback is therefore under development as a complementary approach for stabilization. Uncontrolled longitudinal emittance blow-up is mainly mitigated by the multi-harmonic feedback systems reducing the 40 MHz and 80 MHz impedances in addition to the upgraded direct feedback loops.

Figure 4 shows a typical longitudinal beam profile during the last turn before extraction from the PS, together with the 4σ-bunch length along the batch. At an intensity of

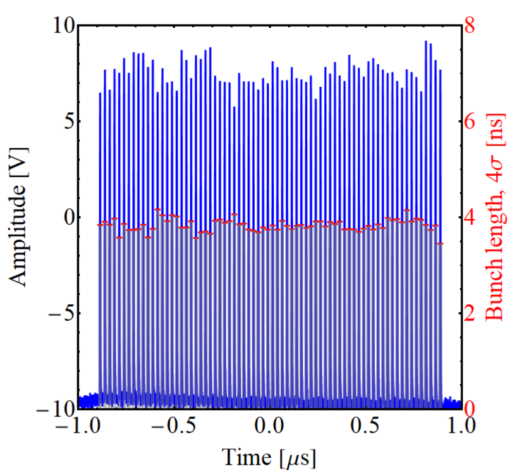

Figure 4: Typical bunch profile of the last turn in the PS (blue) and 4σ-bunch length (Gaussian fit) of the 72 bunches at an average intensity of $2.8 \cdot 10^{11}$p/b (2021 data).

$2.8 \cdot 10^{11}$p/b the longitudinal beam parameters, in particular the bunch length, do not indicate any noticeable degradation of the longitudinal quality of the tail bunches. The effect of transient beam loading during the bunch splittings yet remains small at this intensity.

This is confirmed by analyzing the distribution of the bunch length at extraction during multiple cycles (Fig. 5, top), with an average length below the nominal value of

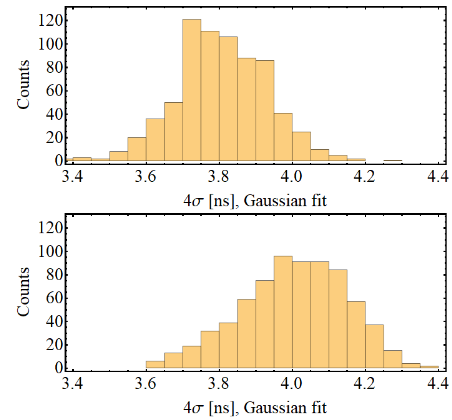

Figure 5: Bunch length (4σ) histogram accumulated over ten extractions (2021 data). The average bunch intensity at extraction was $2.8 \cdot 10^{11}$p/b (top) and $3.1 \cdot 10^{11}$p/b (bottom).

4 ns. Increasing the intensity further to $N_b = 3.1 \cdot 10^{11}$p/b significantly degrades the longitudinal beam quality. The longitudinal emittance growth at the origin of the longer bunches is mostly driven by residual beam induced voltage in the two 80 MHz cavities during the RF manipulations at the flat-top.

CONCLUSION

The nominal intensity for the HL-LHC of $2.6 \cdot 10^{11}$ p/b has been reached at PS extraction in batches of 72 bunches spaced by 25 ns. This achievement is owing to a variety of upgrades of almost all RF systems in the PS. The impedances of the RF cavities are reduced at the source by local feedback systems. As a complementary approach longitudinal beam instabilities are mitigated by dedicated global feedback in combination with increased Landau damping with a higher-harmonic RF system. Thanks to the final RF improvements during the LS2 completing the LIU project scope, a comfortable operational margin has been established, with peak intensities approaching $3 \cdot 10^{11}$ p/b. The fine tuning of the longitudinal parameters and bunch rotation for the PS-SPS transfer has become the next important priority, as well as studies on the source of residual longitudinal tails of the extracted bunches. With the $\varepsilon_l = 3$ eVs bunches regularly injected from the PSB, the longitudinal characteristics during acceleration in the PS approach the original design [9].

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REFERENCES

[1] J. Coupard et al., "LHC Injectors Upgrade, Technical Design Report - Volume I: Protons", CERN-ACC-2014-0337, CERN, Geneva, Switzerland, 2014.

[2] A. Huschauer *et al.*, "Beam commissioning and optimisation in the CERN Proton Synchrotron after the upgrade of the LHC Injectors", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, 2022, this conference.

[3] H. Damerau *et al.*, "RF manipulations for higher brightness LHC-type beams", in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'14)*, Shanghai, China, 2014, p. 2600.

[4] H. Damerau, M. Paoluzzi, "Design of the PS longitudinal damper", CERN-ACC-NOTE-2013-0019, CERN, Geneva, Switzerland, 2013.

[5] F. Bertin, H. Damerau, G. Favia, A. Lasheen, "Active methods of suppressing longitudinal multi-bunch instabilities", *Proc. ICFA mini-Workshop on Mitigation of Coherent Beam Instabilities in Particle Accelerators (MCBI 2019)*, Zermatt, Switzerland, 2019, p. 197.

[6] H. Damerau, D. Perrelet, "New CERN PS 10 MHz cavity one-turn delay feedback hardware and beam tests", *Low-Level Radio Frequency Workshop (LLRF13)*, Lake Tahoe, California, USA, 2013.

[7] F. Bertin *et al.*, "Impedance Reduction of the High-frequency Cavities in the CERN PS by Multi-harmonic Feedback", *Proc. Low-Level Radio Frequency Workshop (LLRF19)*, Chicago, Illinois, USA, 2019, arXiv:1910.06874.

[8] E. Shaposhnikova *et al.*, "Study of Different Operating Modes of the 4th RF Harmonic Landau Damping System in the CERN SPS", in *Proc. 6th European Particle Accelerator Conf. (EPAC'98)*, Stockholm, Sweden, 1998, p. 978.

[9] G. Rumolo *et al.*, "Expected performance in the injectors at 25 ns without and with Linac4, in *Proc. Review of LHC and Injector Upgrade Plans (RLIUP)*, Archamps, France, 2013, p. 17.