THE PROPOSED CERN PROTON-SYNCHROTRON UPGRADE PROGRAM

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Abstract

In the framework of the High-Luminosity LHC project, the CERN Proton Synchrotron (PS) would require a major upgrade to match the future beam parameters requested as pre-injector of the collider. The different beam dynamics issues, from space-charge limitations to longitudinal instabilities are discussed, as well as the proposed technical solutions to overcome them, covering the increase of the injection energy to RF related improvements.

INTRODUCTION

The role of the PS in the production of the beams for the LHC is to preserve at maximum the transverse emittances defined by its injector, the PS Booster (PSB)[1], and to manipulate the longitudinal phase-space to define the bunch spacing required by the collider. In the framework of the the High-Luminosity LHC project, and when the Linac4 will become operational, all the injectors should be able increase the intensity per bunch of the LHC-type beams while keeping or reducing the transverse emittances as defined in [2]. In this paper, the current understanding of the PS limits is briefly reviewed and a summary of the improvements proposed in view of matching the HL-LHC requirements are presented.

LHC BEAM PRODUCTION AND RELATED ISSUES

Injection Flat-Bottom

The production of the high-brightness LHC-type beams is realized by a double-batch injection: a total of six bunches are transferred from the PSB into a harmonic $h = 7$, four of them waiting for 1.2 s on the 1.4 GeV injection flat bottom for the second injection. Then a triple splitting at low energy plus two double splittings on the 26 GeV extraction flat-top result in the 25 ns bunch spacing [3] (see Fig. 1). The last double splitting can be converted into a simple rebucketing, together with a different longitudinal blow-up, if 50 ns bunch spacing is required instead. During the 1.2 s long injection flat bottom, space-charge and headtail instabilities can degrade the transverse beam quality. A too large Laslett space-charge tune-shift, i.e. larger than $\approx$-0.3, can cause a significant emittance blow-up [4] of the first four bunches at low energy. For this reason,

it was proposed in [5], and revised in [1, 6], to increase the PSB extraction energy to 2 GeV and to allow injecting greater beam intensities while conserving the transverse beam characteristics. A series of studies to determine with more precision the maximum Laslett tune-shift acceptable and to optimize the injection working point has been launched [7]. Beam injection at 2 GeV proved to be feasible but with important hardware changes. The injection septum (see Fig. 2 for the new design) and its power converter should be replaced, since the strength of the existing ones would not be sufficient, as well as for the magnets forming the injection bump. A second kicker should be installed to allow the injection of all the non LHC-type beams at higher energy, and to increase the flexibility with beams for the LHC. More details about the proposed injection can be found in [8] and its implementation is eventually foreseen for 2017. Another source of emittance blow-up and losses during the injection flat bottom is a headtail instability [9]. For the current LHC beams, this instability is cured by introducing linear coupling between the two transverse planes. However, the growth rate of headtail instabilities at the flat bottom scales like N_b/γ, with N_b the intensity per bunch and γ the relativistic factor, which translates into >30% faster instabilities in case twice the current intensity would be injected at 2 GeV. In case that linear coupling would no longer be sufficient, an upgrade of the existing transverse feedback (FB) is foreseen. On top of this, a change in the chromaticity at injection and/or the use of existing Landau octupoles would be beneficial. In general,
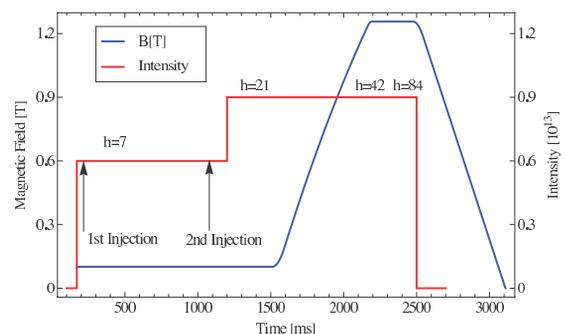

Figure 1: Production scheme for the 25 ns beam with double-batch injection. The RF harmonics are indicated on the plot

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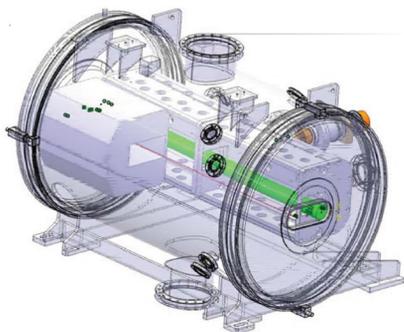
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Figure 2: Conceptual design of the new injection septum

the injection flat-bottom is considered a delicate period in the cycle, where many factors can degrade the transverse emittance. Due to this, and due to the eventual increase of the injection energy, the magnets and power converters of the orbit correctors and quadrupoles dedicated to trim the injection working point are going to be upgraded starting from 2013.

Acceleration and High Energy

During acceleration, transition crossing is considered a delicate period due to the lack of longitudinal focussing. The stability of the upgraded LHC beams was determined by extrapolating the current beam operation: for the longitudinal plane, no limitations would be expected [6]. Fast vertical transverse instabilities were observed for high-intensity single bunch beams (see [10] for the most recent studies). The vertical Transverse Mode Coupling Instability (TMCI) can induce large beam losses or transverse emittance blow-up: the instability threshold however seems to remain above the parameters of the future LHC-beams specified in [2].
As mentioned, once the bunches reach the extraction flat top, they are split in two or four, depending on the final bunch spacing, with a lot of care given to the fact that the final spread in the bunch intensity along the final batch should not be larger than $\pm 10\%$. Finally, the bunches are shortened by a non-adiabatic bunch rotation to match the SPS bucket duration. The different limitations from the PS RF gymnastics and systems are presented in the next section. Before extraction, there is still a possible source of transverse emittance blow-up: electron clouds, in fact, were observed in the past, as reported also in [11]. So far, electron cloud effects did not cause any instability for the nominal LHC beams. However, emittance increase was observed for beams with a bunch length before rotation smaller than 12 ns (4σ) associated with electron cloud [12]. It is suspected, but not confirmed, that electron-cloud was really the source of the instability. Therefore, a campaign of measurement of electron cloud build-up and the study of an eventual threshold instability is foreseen for 2011-2012.

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LONGITUDINAL LIMITATIONS AND PROPOSED CURES

To finally fit into the 5 ns buckets in the SPS, the nominal parameters of LHC-type bunches at PS extraction have originally been fixed to a longitudinal emittance of $\varepsilon_l = 0.35$ eVs with a bunch length of $4\sigma = 4$ ns [3]. The maximum intensity N_b for such bright bunches in the PS is mainly limited by coupled-bunch (CB) instabilities after transition crossing, and the bunch-to-bunch reproducibility suffers from transient beam loading (TBL) during the bunch splitting manipulations [13]. Due to the large number of RF and FBs (24 cavities ranging from 2.8 MHz to 200 MHz), a study phase until 2012 for the RF related upgrades has been started. During this phase, the technical feasibility of cavity impedance reductions by FB improvements is investigated, as well as the source of the present intensity limitations to prioritize hardware upgrades and replacements.

Coupled-Bunch Instabilities

The CB stability limit versus N_b and ε_l is illustrated in Fig. 3. From these observations an empiric scaling of the
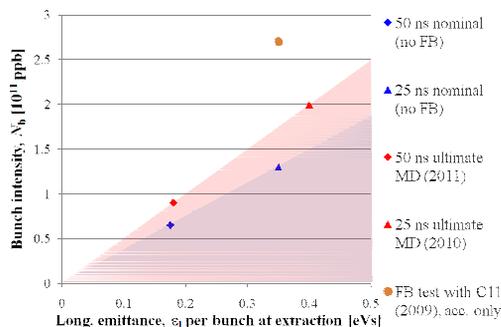

Figure 3: Longitudinal stability limits according to observations from 2009 to 2011. A test using the spare 10 MHz cavity (C11) as FB kicker allowed to accelerate twice the nominal longitudinal density.

CB threshold with N_b/ε_l is suggested. The mode spectrum shows that the CB instabilities are most likely excited by the main 10 MHz accelerating cavities. Three different upgrade paths are thus under investigation: improved direct and 1-turn FBs (1-TFB) around the 10 MHz cavities, a new global CB-FB, potentially with a dedicated kicker, and the possibility of delivering naturally more stable bunches with larger ε_l to the SPS while keeping bunch lengths at 4 ns. However, first PS-SPS transfer studies indicate that ε_l is difficult to increase without larger capture losses in the SPS [14].

Reduction of Transient Beam Loading (TBL)

For the generation of LHC-type beams, the bunches are split multiple times in the PS. At maximum, each injected bunch is divided into $3 \cdot 2 \cdot 2 = 12$ bunches, a process

during which the relative phases between RF systems must be controlled to about $\pm 1^0$. However, as only 6/7 of the PS circumference are filled, each RF system is subject to TBL, modulating its phase along the batch. The resulting modulation of the relative phase between RF systems causes a bunch-to-bunch asymmetry of the splitting, and bunch-to-bunch intensity differences along the batch. To reduce TBL, the possible increase of the direct feedback gain by new FB amplifiers closer to the cavities is being studied. At the same time, it is proposed to equip the 20, 40 and 80 MHz RF systems with 1-TFBs to further reduce their impedance at multiples of the revolution frequency. The hardware for these feedbacks will be based on an LHC digital signal processing board [15], recently modified for the 1-TFB around the PS 10 MHz cavities.

INTERMEDIATE SCHEMES

Next to the main upgrade path, requiring significant hardware improvements, various intermediate schemes are being investigated. Figure 4 shows the measured bunch profiles during an RF manipulation $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$ [16]. Compared to the nominal triple splitting RF gymnastics, where only $4 + 2$ instead of 7 bunches are injected into the PS, starting from $h = 9$ may profit from the full brightness of all four PS Booster rings at every injection. Further schemes accelerating through transition on $h = 7$ or 9, removing the longitudinal acceptance bottleneck at the start of acceleration with $h = 21$, and performing the manipulations around 9 GeV are being investigated.

CONCLUSIONS

A vigorous series of studies has been launched in 2011: an important upgrade of the CERN PS is foreseen in the next 6-7 years to meet the requirements of the High-Luminosity LHC. The program is meant to overcome the major limitations related to the current machine operation, i.e., space-charge effects at injection, transient beam-
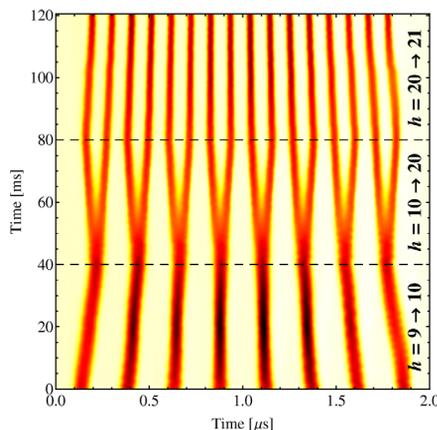
Figure 4: Wall current monitor signal during the transfer of 8 bunches from $h = 9$ to $h = 21$ at 2 GeV.

loading and longitudinal coupled-bunch instabilities for the LHC cycles. For the first issue, the injection energy would be increased from 1.4 GeV to 2 GeV, for the second, a major renovation of the RF system with the introduction of additional and improved longitudinal FBs will be implemented.

REFERENCES

[1] K. Hanke *et al.*, WEPS020, these proceedings

[2] R. Garoby *et al.*, WEPS017, these proceedings

[3] M. Benedikt *et al.*, CERN-2000-003

[4] E. Métral, and H. Burkhardt, "Achievable Space-Charge Tune Shift with Long Lifetime in the CERN PS and SPS", Hadron Beam 2008, Nashville, August 2008, WGA03, p. 48 (2008), and references therein

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

[6] S. Gilardoni *et al.*,"PS Potential Performance with a Higher Injection Energy", Chamonix 2011 LHC Performance Workshop, Chamonix, France, 2011

[7] S. Gilardoni *et al.*, MOPS014, these proceedings

[8] J. Borburgh *et al.*, THPS049, these proceedings

[9] E. Métral *et al.*, CERN-AB-2007-032 and references therein

[10] S. Aumon *et al.*, CERN-ATS-2010-030

[11] E. Mahner *et al.*, Phys. Rev. Spec. Top. Accel. Beams 11 (2008) 094401.

[12] R. Steerenberg *et al.*, FRPMN076, Proceedings of PAC07, Albuquerque, New Mexico, USA, 2007

[13] H. Damerau, S. Hancock, M. Schokker, "Longitudinal Performance with High-density Beams for the LHC in the CERN PS", ICFA-HB2010 Workshop, Mohrschach, Switzerland, 2010

[14] H. Damerau, S. Hancock, "Update on Longitudinal Performance of LHC Beams in the PS", CERN Machine Studies Working Group, CERN, Geneva Switzerland, 2011 (unpublished)

[15] V. Rossi, WE5PFP076, Proceedings of PAC09, Vancouver, BC, Canada, 2009

[16] C. Carli et al., "Alternative/complementary Possibilities", Chamonix 2011 LHC Performance Workshop, Chamonix, France, 2011

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