OTHER MEANS TO INCREASE THE SPS 25 ns PERFORMANCE – TRANSVERSE PLANE

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Abstract

The LHC Injectors Upgrade (LIU) project aims at extending the brightness and intensity reach of the injector complex. After the implementation of all LIU upgrades, beam loading and longitudinal instabilities in the SPS will likely remain the main limitations for the achievable intensity of the 25 ns beam. The goal of this paper is to present options to circumvent this limitation and increase the intensity of the 25 ns beams out of the SPS. In particular, two aspects will be addressed: 1) Alternative SPS optics configurations with intermediate transition energy between Q20 and Q26. Although the presently operational Q20 optics pushed the TMCI threshold from 1.6×10^{11} p/b to 4×10^{11} p/b, it might not be the optimal choice for maximizing the intensity of the 25 ns beam due to the RF power limitations. Possible optics configurations with intermediate transition energy are investigated, aiming at a better balance between TMCI threshold and RF power requirements. 2) Increase of the number of colliding bunches in the LHC by transferring a larger number of bunches between the PS and the SPS. In this context, schemes for transferring 80 or more bunches per PS batch and their operational implications are discussed, together with possible advantages for mitigating other limits in the SPS and LHC. Finally, machine development studies during Run 2 for evaluating the feasibility and potential of these schemes are addressed.

INTRODUCTION

The LHC Injectors Upgrade (LIU) project aims at extending the brightness and intensity reach of the injector complex in view of the beam parameters requested by the High Luminosity LHC (HL-LHC) project [1]. After the implementation of all LIU upgrades the performance of the injectors will match the HL-LHC requirements in terms of beam brightness. However, despite the significant increase of the achievable beam intensity expected from the LIU upgrades of the SPS RF system [2], reaching the HL-LHC target beam intensity of 2.3×10^{11} p/b with 25 ns beams will still remain challenging due to beam loading and longitudinal instabilities in the SPS at high energy [3].

In what follows, two possible options for circumventing this limitation will be presented. The focus here is put on the transverse plane. Possible options for the longitudinal plane are discussed in Ref. [4].

SPS OPTICS WITH INTERMEDIATE TRANSITION ENERGY

The first option for mitigating intensity limitations along the SPS ramp consists of an SPS optics with a gamma at transition γ_t in between the Q26 optics used in the past and the Q20 low γ_t optics [5], which is operational for LHC beams since October 2012. The main motivation for implementing the Q20 optics came from the Transverse Mode Coupling Instability (TMCI) at injection: In Q26, the measured TMCI threshold for bunches injected with the nominal longitudinal emittance $\varepsilon_l = 0.35$ eVs is at around $N_{th}\approx1.6\times10^{11}$ p/b for vertical chromaticity close to zero. As expected from analytical scaling laws, the threshold is raised to more than $N_{th}\approx4.0\times10^{11}$ p/b in the Q20 optics due to the lower transition energy, i.e. $\gamma_t = 18$ instead of $\gamma_t = 22.8$, and the resulting increase of the phase slip factor $\eta\equiv1/\gamma_t^2-1/\gamma^2$ (LHC beams are injected above transition) [6]. Furthermore, for a given longitudinal emittance, the Q20 optics provides also better beam stability in the longitudinal plane compared to the Q26 optics. However, in order to achieve the same bucket area, higher RF voltage and consequently more RF power are needed in the Q20 optics, especially during the first part of the ramp. A new SPS optics with intermediate transition energy in between the Q20 and the Q26 optics could therefore help to reduce the required RF power during acceleration. With the Q20 optics the achievable intensity may remain limited, even after the foreseen LIU upgrade of the SPS RF power [2] and after reducing the acceleration rate. Furthermore, additional flexibility in the choice of transition energy could be useful for optimizing the machine performance in case the longitudinal instability scaling is less favourable for the Q20 optics than assumed so far [4]. On the other hand, such a new optics must provide enough margin with respect to the TMCI threshold in order to allow for stable beam operation with 25 ns beams of about $N\approx2.6\times10^{11}$ p/b at injection, as required for achieving the HL-LHC target intensity at SPS flat top.

The transition energy in the SPS is determined by the choice of the horizontal betatron tune as shown in Fig. 1. For Q_x close to multiples of the machine super period of 6, resonant dispersion waves with large amplitude are excited around the ring resulting in the asymptotic behaviour of γ_t [7]. These working points are not suited for regular machine operation. On the other hand, an interesting option

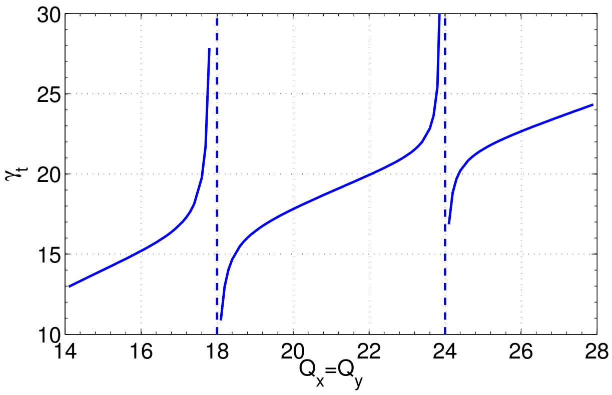

Figure 1: Gamma at transition as a function of the betatron tunes in the SPS.

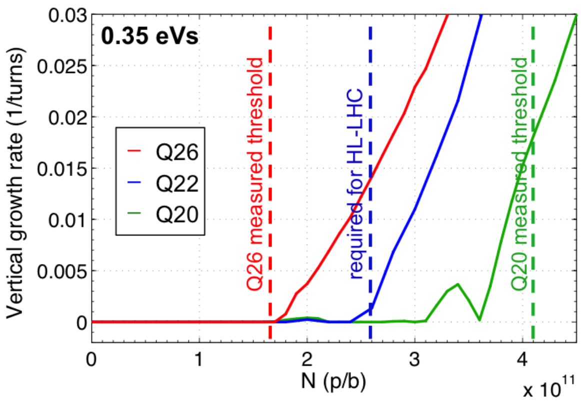

Figure 2: Simulated vertical growth rates as function of intensity for different SPS optics.

for an intermediate transition energy is achieved for working points around $Q_x \approx 22$, for which $\gamma_t \approx 20$: Assuming the well established fractional tunes for LHC beams, the "Q22" optics with $(Q_x, Q_y) = (22.13, 22.18)$ [8] has a similar structure of low-order resonances around the working point as the Q20 and Q26 optics. Furthermore, the Q22 optics provides sufficient aperture for LHC beams and the rematching of the TT10 injection transfer line optics is feasible. The rematching of the extraction transfer lines TI2 and TI8 towards the LHC has not been looked into yet, but is expected to be also feasible. It should be pointed out that the Q22 optics has about twice higher dispersion at the location of the RF cavities compared to Q26 and Q20. Although not expected, this could potentially cause problems because of synchro-betatron resonances.

The TMCI intensity threshold to be expected in the Q22 optics was studied in macroparticle simulations using the HEADTAIL code. The simulations are based on the SPS transverse impedance model [9], which is obtained by summing the contributions of the different devices along the machine weighted by the β-functions at their respective locations. The model includes the SPS kickers, the resistive wall impedance, the BPMs, the RF cavities and the flanges and the transition pieces between the different vacuum chamber types. It has been benchmarked with measurements and reproduces more than 90% of the vertical coherent tune shift and of the headtail growth rate of mode 0 for negative chromaticity, as well as the TMCI thresholds in the Q20 and Q26 optics for different longitudinal emittances [10, 6]. In addition to the operational setting of $Q'_y = 1$ for the linear chromaticity, the non-linear chromaticity up to third order as obtained from machine experiments was used in the simulations for the Q20 and Q26 optics [11]. Only linear chromaticity with a setting of $Q'_y = 2$ was used for the Q22 optics, since there are no reliable estimations of the non-linear chromaticity available. The solid lines in Fig. 2 show the simulation results for the TMCI growth rate as a function of intensity in the different SPS optics configurations for the case of the nominal longitudinal emittance at injection $\varepsilon_l = 0.35\,\mathrm{eVs}$ and scaled RF voltages for maintaining the same bucket area for the different transition energies. The vertical dashed lines show the experimentally observed instability threshold for the Q26 and the Q20 optics as well as the required intensity for reaching the HL-LHC target. Excellent agreement with the simulation model is observed for the Q26 optics. For the Q20 optics the onset of the instability predicted by the model is slightly below the measured threshold, i.e. the prediction is conservative. As expected, the simulations for the Q22 optics predict an intermediate instability threshold, which is very close to the intensity required for reaching the HL-LHC target.

The following key studies for demonstrating the Q22 optics as viable alternative to the baseline Q20 optics have been identified:

- Measurement of the TMCI threshold in the Q22 optics and verification of sufficient intensity margin for reliable production of the HL-LHC target beam parameters. Possible gain from a reduction of the vertical beam coupling impedance, e.g. by removing the MKE extraction kickers in LSS4 only needed for CNGS-like extraction.
- Experimental verification that indeed higher intensities with sufficient longitudinal stability at flat top can be reached with the Q22 optics in case the RF voltage and RF power required in the Q20 optics remain an intensity limitation after the 200 MHz RF upgrade.
- Resonance behaviour for high brightness LHC beams in comparison to Q20 and Q26. Possible impact from synchro-betatron resonances due to the larger dispersion in the locations of the RF cavities in Q22.
- Rematching of the TI2/TI8 transfer lines to the LHC including the SPS extraction bumps for the Q22 optics.
- Effect of injection dogleg on closed orbit and dumped beam trajectory in the Q22 optics.

80 BUNCH SCHEME

The yearly integrated luminosity in the LHC will be limited by the pileup in experiments, the LHC availability and the number of colliding bunches. The nominal LHC 25 ns filling scheme is based on the injection of trains of 4 (or 2)×72 bunches from the SPS [12], where the gap length between the individual batches of 72 bunches is determined by the rise time of the SPS injection kickers (225 ns) and the flat top length of the SPS extraction kickers and LHC injection kicker limits the total length of the injected bunch train. The gap between these trains in the LHC is determined by the LHC injection kicker rise time (900 ns). The LHC dump kicker rise time (3000 ns) defines the length of the abort gap. As such the standard filling scheme for 25 ns beams allows for 2736 colliding bunches in the main LHC experiments at IP1 and IP5 plus 12 non-colliding bunches per beam as requested by the experiments for background calibration.

A possible way of improving the performance of the 25 ns beam is to increase the number of colliding bunches in the LHC, which can be achieved by increasing the number of bunches transferred from the PS to the SPS. In fact, in an early version of the LHC 25 ns filling scheme it was foreseen to generate 84 bunches at PS flat top by adiabatic debunching of 16 bunches followed by recapture on harmonic $h = 84$ and extract only 81 of them while deliberately losing 3 bunches due to the PS extraction kicker rise time [13]. First experiments with this beam were performed in 2000, where even 82 bunches were injected into the SPS [14]. Due to problems with longitudinal beam stability at PS flat top [15], this scheme was replaced by the nominal production scheme [12], nowadays also referred to as "standard scheme", in which a train of 72 bunches is produced in the PS by injecting 4+2 PSB bunches into harmonic $h = 7$, followed by a triple splitting at low energy and two double splittings at flat top before extraction at $h = 84$. Besides the improved beam stability at PS flat top, this scheme provides a gap in the bunch train to allow for a clean beam transfer to the SPS. However, the PS extraction kicker has a rise time (1-99%) of only 89 ns, which would allow for a clean extraction of up to 81 bunches. Recently, a scheme for producing trains of 80 bunches in the PS has been proposed [16]. Figure 3 shows a sketch of the required beam manipulations during the PS cycle. All RF gymnastics are identical to the standard production scheme (thus the same brightness as for the standard scheme [1] can be expected). However, the starting point is that 4+3 instead of 4+2 bunches are injected into the PS at harmonic $h = 7$, i.e. the machine needs to be completely filled. After acceleration to an intermediate plateau of 2.5 GeV for the triple splitting, one out of the resulting 21 bunches is eliminated from the train by gated excitation with the transverse damper. The remaining 20 bunches are accelerated to flat top and twice double split into 80 bunches. In principle, the bunch removal could be done also at higher energy and after the final bunch splittings, which would provide additional flexibility to produce bunch trains of 80, 81 or even 82 bunches. However the low energy option is preferred due to the following advantages:

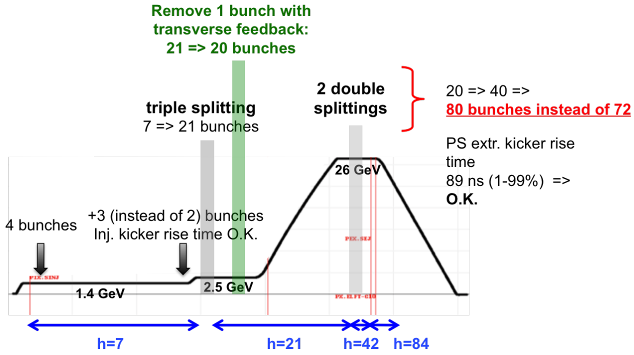

Figure 3: Sketch of the proposed scheme for the production of 80 bunches in the PS.

- The transverse damper power amplifiers presently installed in the PS provide sufficient power (0.8 kW in CW) to induce large transverse oscillations at 2.5 GeV and sufficient band-width (23 MHz at -3 dB) at harmonic $h = 21$ in order to excite a single bunch without affecting neighbouring bunches.
- It is better to lose particles at low energy in order to minimise the activation of the machine. Furthermore, the PS low energy correctors can be used to create an orbit bump and thus an artificial aperture restriction in order to localize the beam losses at one position in the machine, e.g. the new dummy septum which was installed in Straight Section 15 in order to protect the extraction septum SMH16 during the Multi-Turn Extraction (MTE) of SPS fixed target beams [17].
- The largest number of colliding bunches in the LHC is achieved with 80 rather than with 81 or 82 bunches per PS extraction.

Possible LHC filling schemes based on the transfer of 80 bunches from the PS to the SPS have been studied. With 4×80 bunches per LHC injection plus a single injection of 12 bunches per ring it should be possible to achieve a maximum of 2892 colliding bunches in IP1/IP5. If the LHC experiments prefer to have a few non-colliding bunches, the maximum number of bunches colliding in IP1/IP5 would be 2880, which is still 5% more compared to the present 25 ns filling scheme and directly translates into an increase of the integrated luminosity. It is presently under investigation if the flat-top lengths of the SPS extraction kickers (MKEs) and the LHC injection kickers (MKIs) are sufficient for the transfer of 4×80 bunches, or if modifications of the pulse forming networks (PFNs) would be required. Furthermore, it should be emphasized that the transfer of 320 instead of 288 bunches and the corresponding increase of the total beam intensity has strong implications for the

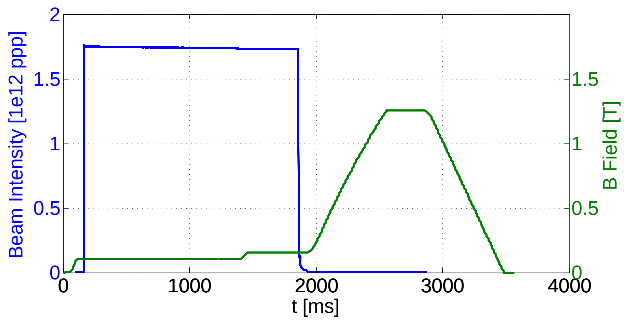

Figure 4: Elimination of a triple split PSB bunch by excitation with the PS transverse feedback at 2.5 GeV.

specification of the SPS beam dump and the protection devices in the transfer lines (TCDIs) and the LHC injection regions (TDIs). It is therefore interesting to note that with 3×80 bunches per LHC injection, up to 2732 colliding bunches in IP1/IP5 (or 2720 with few non-colliding bunches) can be achieved, which is almost the same number as in the present filling scheme. This option could thus also be considered as a back-up in case of limitations of total intensity per SPS-to-LHC transfer (e.g. LHC protection devices, SPS beam dump, SPS RF power, . . .).

First machine development studies in view of the 80 bunch scheme have been performed with single bunch beams. Figure 4 shows the promising result: It was demonstrated that a triple split PSB bunch can be almost completely eliminated by a sinusoidal excitation with the PS transverse feedback system in open loop on the 2.5 GeV plateau of a 3 basic period cycle when reducing the horizontal chromaticity from $\xi_h = -0.8$ to -0.1. Unfortunately it is not yet possible to excite only a selected bunch within a bunch train. This requires a new firmware for the digital card controlling the feedback. Furthermore, a bunch synchronous trigger is needed in order to gate the damper gain.

Once the required firmware and hardware modifications are implemented, the following machine development studies will be performed in order to fully demonstrate the feasibility of the 80 bunch scheme and to address possible issues:

- Elimination of a single bunch with the feedback system in closed loop but with inverted gain.
- Elimination of a selected bunch out of a bunch train. Verification that neighbouring bunches are not affected by measurements of the bunch-by-bunch emittance in the SPS.
- Localization of losses on the dummy septum in SS15 with the help of a closed orbit bump.
- Beam transfer of 80 bunches to the SPS and check of the level of "ghost" bunches potentially created in case of insufficient bunch elimination in the PS. Check the possibility to eliminate bunch residuals with rising edge of PS extraction kicker pulse.
- Study of the impact on longitudinal stability in the PS and SPS.
- Determine the maximum acceptable flat top lengths of the SPS MKEs and the LHC MKIs with low intensity beams (within the safe beam limit).
- Study of potentially enhanced electron cloud effects in the LHC, the SPS and also at PS flat top.

SUMMARY AND CONCLUSIONS

The SPS Q22 optics with intermediate transition energy could help to reduce the required RF power during acceleration. However, it needs to be verified that it allows to reach higher intensities compared to the Q20 optics with sufficient longitudinal stability at flat top and that it provides sufficient intensity margin with respect to the TMCI threshold in order to guarantee reliable production of the HL-LHC target beam parameters.

The 80 bunch scheme seems very promising, as it allows to increase the integrated luminosity by more than 5% for the same pile-up limit through a larger number of colliding bunches compared to the present LHC filling scheme, or alternatively to reach the same number of colliding bunches in the LHC with a maximum of only 240 bunches per transfer from the SPS. This could be already interesting for boosting the performance or to mitigate existing limitations during the LHC Run 2. The validation of the 80 bunch production scheme in the PS will be performed in machine development studies as soon as the necessary firmware and hardware modifications are implemented.

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