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LOWER-HARMONIC RF SYSTEM IN THE CERN SPS

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Abstract

Significant beam losses increasing with intensity are observed at capture and along the SPS flat bottom for the LHC-type proton beams. The intensity should be doubled for High-Luminosity LHC and high losses may be a major performance limitation. Bunches extracted from the PS, the SPS injector, are produced in a 40 MHz RF system applying a bunch rotation at the end of the cycle and therefore cannot be perfectly matched to the 200 MHz SPS RF bucket. The possibility of using a lower-harmonic, additional RF capture system in the SPS was already proposed after the LEP era in preparation for transfer of the nominal LHC beam but the bunch rotation was the preferred solution, since the induced voltage in the SPS 200 MHz RF system would be too large to ensure stability in a low harmonic system without mitigation measures. However, the use of the upgraded one-turn delay feedback and the 200 MHz RF system as a Landau cavity could help to improve beam stability. The feasibility of this scenario to reduce capture losses in the SPS is analysed and presented in this paper. The beam transfer to the main 200 MHz RF system is simulated using a realistic bunch distribution.

INTRODUCTION

The increasing beam losses with intensity at flat bottom in the Super Proton Synchrotron (SPS) are a bottleneck for the production of the High-Luminosity LHC (HL-LHC) proton beams since the nominal intensity of 1.2×10^{11} particles per bunch (ppb) must be doubled [1]. The bunches injected into the SPS are created in the PS with a 40 MHz RF system and rotated with an additional 80 MHz RF system before extraction to the SPS [2]. Therefore, no bunch-to-bucket matching in the 200 MHz SPS RF system can be achieved and the bunch population at large synchrotron amplitudes is too dense to avoid losses due to any perturbations after injection and at the start of acceleration [3]. To reduce the number of particles injected close to the RF separatrix, the longitudinal acceptance can be increased by introducing a lower-harmonic RF system. However, the present acceleration system must be preserved to allow production of short bunches for the LHC. Due to their large bandwidth, the 200 MHz travelling wave cavities are able to accelerate both ions and protons [4]. Further the 800 MHz RF system is essential in preserving beam stability throughout the cycle [5].

The possibility of adding a lower-harmonic RF system for bunch capture in the SPS had been already studied when the injector chain was prepared for the LHC-type beams [6]. Beam-loading in the 200 MHz RF system and coupled-bunch instability at flat bottom were considered as too serious limitations for beam stability and bunch compression in PS had been preferred at that time. Today the SPS 200 MHz RF system undergoes significant upgrades [1, 7] which allow the feasibility of this loss mitigation scheme to be revisited. The upgraded one-turn delay feedback will decrease the beam-loading by an additional factor of two and the experience gained with the Landau cavity at 800 MHz can also be used [1, 8, 9].

The power available per 200 MHz cavity after RF upgrade will be raised to 1.05 MW for the three-section cavities and 1.6 MW for the four-section cavities [7]. To avoid particle loss at the beginning of acceleration the RF program is usually designed to keep a constant bucket filling factor in momentum q_p. Therefore, the available RF power together with beam-loading effect defines a maximum longitudinal emittance that can be accelerated. For HL-LHC intensity, larger bunch emittance than the nominal (0.35 eVs) will be considered since beam stability should be improved in the PS which suffers from coupled-bunch instability [10]. With a filling factor of $q_p = 0.8$ the maximum possible emittance is 0.42 eVs. A larger filling factor could still be acceptable depending on the loss budget allowed and the PS particle distribution but this value, based on present operational experience, will be used in what follows—together with the nominal emittance—to determine the characteristics of the lower-harmonic RF system. The initial bunch distributions are obtained from simulations at the PS flat top without intensity effects, in agreement with measurements and a nominal RF program.

CHOICE OF RF FREQUENCY

The SPS capture system must provide a sufficiently large bucket length without degrading beam stability for bunches produced in the PS without rotation. Measurements of bunches adiabatically shrunk at PS flat top have shown that a minimum bunch length of 6 ns for nominal intensity can be obtained at extraction to the SPS. Longer bunches would require to control the 200 MHz induced voltage to a very low level. Figure 1 shows the bucket length for different choices of RF frequency together with the maximum bunch length for a momentum filling factor of 0.8. Frequencies are restricted to multiples of 40 MHz due to 25 ns spacing of LHC bunches. Only RF systems at 40 MHz and 80 MHz ensure a sufficiently large bucket length. However, for fixed emittance beam stability is reduced in both cases. Indeed, present nominal LHC-type beam is at the limit of stability on SPS flat bottom. For a constant bunch length both thresholds, for loss of Landau damping and coupled-bunch instability, scale as $(\epsilon_l h)^2$ with ϵ_l the longitudinal emittance and h the harmonic number [11], so only a 80 MHz RF system is suit-

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able on SPS flat bottom. Simulations of this scenario for a train of 48 bunches (Fig. 2) using code BLonD [12] exhibit for nominal emittance an intensity threshold significantly bellow the HL-LHC intensity. The 80 MHz voltage was fixed to V_{80} = 1.1 MV (see below). A standard SPS bunch train contains 72 bunches but similar stability limits were obtained with SPS impedance model [13] for a batch of 48 bunches which allows the simulation time to be reduced.

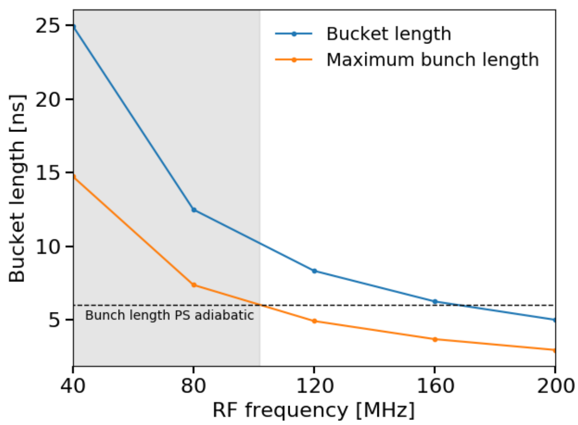

Figure 1: Bucket length and maximum bunch length for a filling factor q_p = 0.8 and different RF frequencies of an SPS capture system.

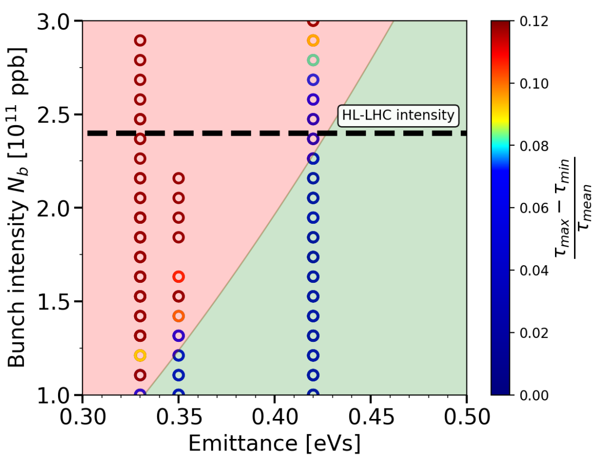

Figure 2: Stability threshold at the SPS flat bottom in a single 80 MHz RF system with V_{80} = 1.1 MV and the SPS impedance model after the LIU upgrades but without the impedance of the 80 MHz RF system. Colours represent the maximum relative amplitude of the bunch length oscillations during a 10 s flat bottom.

RF VOLTAGE AT CAPTURE

To minimise particle loss during transfer to the 200 MHz bucket the emittance should not increase at capture. Bunch length is reduced adiabatically afterwards to fit the bunches into the 200 MHz RF bucket. Bunches simulated in PS without rotation have a bunch length at extraction of 5.3 ns and 5.8 ns for the nominal and 0.42 eVs emittance respectively. The difference from measured 6 ns at nominal intensity can be explained by uncontrolled emittance blow-up in PS due to intensity effects. For use as a Landau system the maximum 200 MHz voltage in the SPS is

$$V_{200} = \frac{h_{80}}{h_{200}} V_{80}. \quad (1)$$

Matched 80 MHz voltage in the double RF system of 80 MHz and 200 MHz is respectively 0.76 MV and 0.89 MV for the two bunch lengths. Due to intensity effects, a higher voltage is required which can be determined in simulation including the full SPS impedance model after LIU upgrade [1, 13–15]. In simulations the position of each of the 48 bunches spaced by 25 ns was matched with intensity effects and therefore, the voltages obtained represent a lower limit to what will be needed in operation. At the HL-LHC intensity of 2.4×10^{11} a voltage of 1.15 MV is required, see Fig. 3.

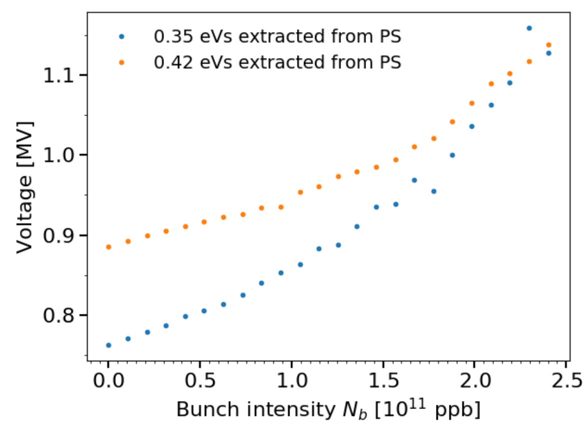

Figure 3: The matched 80 MHz capture voltage required in simulations in a double RF system to compensate for intensity effects and conserve the bunch length injected from the PS. The nominal and maximum emittances with q_p = 0.8 are considered. The 200 MHz voltage in bunch-shortening mode is defined by Eq. (1).

BEAM STABILITY AT FLAT BOTTOM

The residual beam-loading in the 200 MHz cavities is not negligible for HL-LHC intensity even with the upgraded one-turn delay feedback in operation. For the SPS impedance after LIU upgrade beam stability cannot be guaranteed in a single 80 MHz RF system at SPS flat bottom, see Fig. 2. Already from injection, the 200 MHz RF system could be used to increase the synchrotron frequency spread and thus enhance the Landau damping mechanism. The bunch-shortening mode (both RF system in phase, as needed for the rebucketing) was considered because it provides stability in the present SPS double RF operation [9].

The stability thresholds have been simulated using 80 MHz voltage of 1.1 MV for 48 bunches spaced by 25 ns, see Fig. 4. The 200 MHz impedance is reduced according

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to the effect of one-turn delay feedback. The position of the bunches produced in the PS coincides with the SPS RF synchronous phase including intensity effects. With the 200 MHz RF in bunch-shortening mode and $V_{200} = 0.44$ MV, beam stability is significantly improved compared to single RF case. The intensity threshold is above HL-LHC intensity with sufficient margins for all emittances in the range of interest. To determine the optimal beam parameters for HL-LHC intensity a more detailed study of the effect of the 80 MHz impedance and other RF settings (voltage ratio and phase) is necessary.

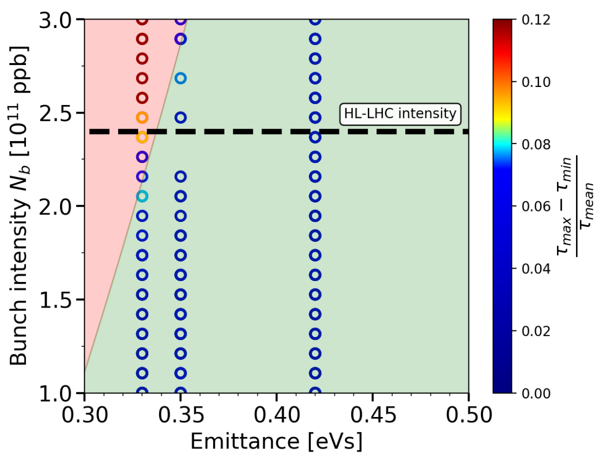

Figure 4: Stability threshold at the SPS flat bottom in a double 80 MHz and 200 MHz RF system in bunch-shortening mode with the full SPS impedance model after the LIU upgrades but without the impedance of the 80 MHz RF system. For every intensity, $V_{80} = 1.1$ MV and $V_{200} = 0.44$ MV. Colours represent the maximum relative amplitude of the bunch length oscillations during a 10 s flat bottom.

BEAM TRANSFER TO THE MAIN RF SYSTEM

To re-capture the bunch in the 200 MHz RF bucket, the bunch length has to be reduced significantly to reach a value of 2.9 ns for a constant filling factor $q_p = 0.8$. For the nominal and large emittance it corresponds to a 80 MHz voltage of 1.90 MV and 2.73 MV respectively. Simulations for zero bunch current show a transfer from 80 MHz to 200 MHz RF buckets without particle loss. However, intensity effects could drive particles outside the 200 MHz bucket.

The re-capture voltage program is designed by adiabatically increasing V_{80} to its maximum value with $V_{200} = 0.4 \times V_{80}$ and $V_{800} = 0.1 \times V_{200}$. Then, the voltage at 200 MHz is increased to complete the transfer with a value computed for $q_p = 0.8$, and V_{80} is reduced to zero. Losses observed during this process are insignificant, see Fig. 5, but lead to creation of ghost bunches in neighbouring buckets, harmful for LHC even at very low level (10^{-3}). The injection voltage V_{80} has been scanned and increase in particle loss is observed at transfer for voltages above the matched value (from Fig. 3) due to longer tails after filamentation or different particle distribution (Fig. 5). Tails in the PS bunch distribution for HL-LHC intensity can potentially further increase population of satellite bunches and the transfer of the 0.42 eVs emittance may require a 80 MHz voltage even higher than 3 MV. The total amount of losses before acceleration can be potentially decreased, especially if they are mainly related to bunch shape extracted from PS after rotation. Simulations including acceleration in the SPS would be needed to confirm the gain from such a system.

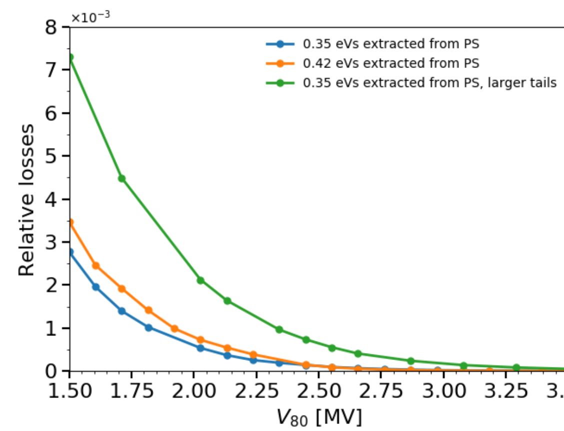

Figure 5: Relative losses in function of maximum V_{80} for 0.35 eVs and 0.42 eVs emittance beam. The intensity is fixed to $N_b = 2.4 \times 10^{11}$ ppb and V_{80} at injection is 1.3 MV. The distribution with larger tails is binomial (see definition e.g. in Ref. [2]) with exponent of 5.

CONCLUSION

The preliminary analysis shows the feasibility of the lower-harmonic RF system scenario in the SPS after the 200 MHz RF upgrade. Capture losses can be decreased by using a 80 MHz RF system simultaneously with the 200 MHz RF system in bunch-shortening mode to ensure beam stability up to HL-LHC intensity. For capture, the voltage of the new system must reach at least 1.15 MV. However, for transfer of 0.42 eVs emittance beam to the 200 MHz RF system the voltage at 80 MHz must be above 3 MV. The impedance of the new RF system was not yet included in simulations. The expected reduction in losses will be significant only if they are mainly related to the bunch shape extracted from PS. Study of the full cycle would be necessary in future to determine accurately the potential gain of such a system. An additional RF system will however increase the overall complexity of the SPS RF systems due to additional RF manipulations.

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