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IMPROVEMENT OF THE LONGITUDINAL BEAM TRANSFER FROM PS TO SPS AT CERN

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Abstract

The beam transfer from the Proton Synchrotron (PS) to the Super Proton Synchrotron (SPS) at CERN is a critical process for the production of beams for the Large Hadron Collider (LHC). A bunch-to-bucket transfer is performed with the main drawback that the rf frequency in the SPS (200 MHz) is five times higher than the one in the PS (40 MHz). The PS bunches are therefore shortened non-adiabatically before extraction by applying a fast rf voltage increase (bunch rotation) to fit them into the short rf buckets in the SPS. However, particles with large amplitude of synchrotron oscillations in the PS longitudinal phase space are not properly captured in the SPS. They contribute to losses at the injection plateau and at the start of acceleration in the SPS. In this contribution, we present measurements and simulations performed to identify the source of the uncaptured particles. The tails of the particle distribution were characterized by applying longitudinal shaving during acceleration. Furthermore, the rotated bunch distribution was improved by linearizing the rf voltage using a higher-harmonic rf cavity.

INTRODUCTION

One of the requirements of the High Luminosity-LHC (HL-LHC) project at CERN is to double the beam intensity. This target is challenging for the injectors, which are being upgraded in the framework of the LHC Injector Upgrade (LIU) project. The PS is the second synchrotron in the injector chain and accelerates the beam up to $p = 26$ GeV/c before extraction to the SPS. The present nominal beam intensity extracted from the PS for the LHC is $N_b = 1.3 \times 10^{11}$ protons per bunch (p/b), and the LIU target is $N_b = 2.6 \times 10^{11}$ p/b with the same longitudinal emittance. The budget for losses in the SPS (including transverse scraping) was set to 10% to extract $N_b = 2.3 \times 10^{11}$ p/b to the LHC [1].

An important limitation to reach the HL-LHC goals are the losses on the SPS flat bottom, which increase with the beam intensity [2]. Losses are a bottleneck to the maximum intensity transmitted in the SPS, and are expected to be larger than the budget foreseen in the LIU baseline. Studies are ongoing to identify the main sources of losses in the SPS. This paper is dedicated to the study of the losses due to the longitudinal distribution of bunches coming from the PS.

The main rf frequency before extraction in the PS is 40 MHz while it is 200 MHz at injection in the SPS. The SPS rf buckets are shorter and a bunch compression is required in the PS prior to extraction. The bunch shortening is performed non-adiabatically in two steps: by a fast increase of the rf voltage of the 40 MHz cavity to 300 kV, followed

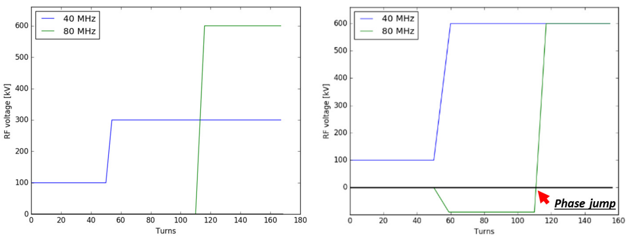

Figure 1: Rf voltage programs for bunch rotation: nominal bunch rotation (left) and with the linearization of the rf voltage (right). The program consists of two steps: first step pulsing only 40 MHz cavities followed by a second step pulsing 80 MHz cavities as well.

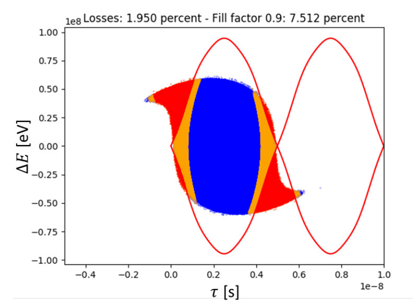

Figure 2: Longitudinal particle distribution in the $(\tau, \Delta E)$ phase space at injection with 4.5 MV rf voltage in the SPS, after bunch rotation in PS. The particles in blue are captured by the SPS rf bucket, the ones in orange are close to the separatrix (filling factor $\Delta E/E_{\mathrm{bucket}} = 0.9$) and could be lost due to transient effects in the SPS, the particles in red are out of the separatrix and lost.

by a fast increase of the rf voltage of two 80 MHz cavities to 300 kV each as shown in Fig. 1 (left) [3]. This operation is called bunch rotation since the longitudinal distribution is rotated during one quarter synchrotron period in phase space, allowing to shorten the bunch length ($\tau_L = 4\sigma$) from 14 ns to 4 ns. However, tails will not fully fit in the SPS rf buckets due to the non-linearities of the PS rf voltage. Particles with large oscillation amplitude have a lower synchrotron frequency and rotate slower in phase space, leading to bunches with "S-shape" as illustrated in Fig. 2.

Studies performed to improve the bunch rotation showed that using the second 40 MHz cavity (previously kept as a spare) allows to reduce the S-shape of the bunch and hence decrease the losses in the SPS by a factor two for nominal bunch intensity [4]. This also reduced the amount of particles captured in neighboring rf buckets (satellites). The second 40 MHz cavity is now used in operation, but is not

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sufficient to reduce losses in SPS below the budget of the LIU project. Methods to further improve of the bunch rotation were attempted and a better characterization of the longitudinal distribution in PS was performed.

LINEARIZATION OF THE RF VOLTAGE DURING BUNCH ROTATION

A possibility to further improve the bunch rotation is to linearize the rf voltage using higher harmonics of the main rf system, hence linearizing the synchrotron frequency of the particles [5]. During the first step of the bunch rotation when the 40 MHz cavities are pulsed, the 80 MHz cavities can be used in bunch lengthening mode to linearize the rf voltage. Concerning the second step, no higher harmonic is available in PS to linearize the rf voltage. Although 200 MHz cavities are available in PS for controlled emittance blow-up, they presently do not have the necessary beam control for this kind of operation.

The rf program used for tests during machine development session is shown in Fig. 1 (right). The phase of the 80 MHz cavities is adjusted to bunch lengthening mode during the first step of the bunch rotation and need to be set back to bunch shortening mode for the second step. To do so, a fast phase switch was implemented in the beam control of the 80 MHz cavities, allowing to move the phase in less than five revolution periods. The rf voltage needs to be adjusted depending on the longitudinal emittance of the bunch (ε_L = 0.35 eVs), and a good compromise was found for 90-100 kV distributed with the two 80 MHz cavities. During the fast phase change, the cavities have to pulse with an offset in frequency and the maximum rf voltage is reduced during this operation.

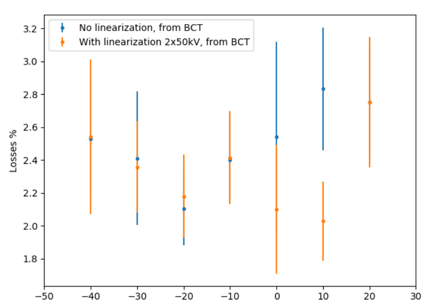

Figure 3: Losses measured by the SPS DC BCT with and without the linearization of the rf voltage. The timings between the two steps of the rf program was scanned with respect to the nominal setting (see Fig. 1).

Measurements were performed with the nominal beam from PS (72 bunches with $N_b = 1.3 \times 10^{11}$ p/b). Losses were measured in the SPS using a DC Beam Current Transformer (BCT), comparing the injected intensity with the one after the start of acceleration in SPS. Results are shown in Fig. 3. The timing between the two steps of the rf program was scanned to find the optimal settings with and without the linearization of the rf voltage. The improvement in terms of losses comparing the optimal settings for both cases is small (less than 0.2%) and within the error bars representing the shot-to-shot variation.

Measurements were also performed applying the linearization of the rf voltage and using the three 80 MHz cavities available in PS, the third one being normally used for ion operation in PS and mechanically short-circuited during normal proton operation. Note that measurements were done only with 48 bunches since the impedance of the third 80 MHz is responsible for uncontrolled longitudinal emittance blow-up [6]. Results are shown in Fig. 4. The absolute losses are higher with respect to the ones in Fig. 3 since a cycle with a longer flat bottom was used in the SPS, leading to more losses at low energy. The relative variation of losses due to the changes in the PS still gives relevant information. With adjustments on the relative time between the two steps of the rf program, losses were reduced by 1%, a small but non-negligible improvement.

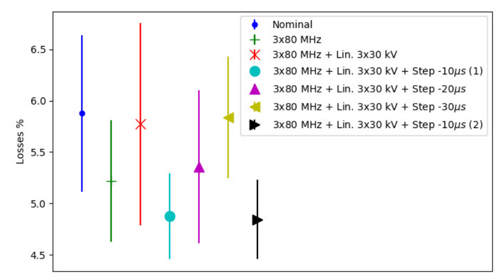

Figure 4: Losses in the SPS for beam produced using in the PS all three 80 MHz cavities and linearization of the rf voltage. The timing between the two steps of the rf program was scanned (see Fig. 1).

Particle simulations were performed using the BLonD code [7] to evaluate the expected gain in terms of losses applying the linearization of the rf voltage. The rf program in Fig. 1 (right) was used, together with an input particle distribution matched to the rf bucket with a binomial line density $\lambda = \lambda_0 \left[1 - 4\left(\tau/\tau_L\right)^2\right]^\mu$, where λ_0 is a normalization factor, and μ is an exponent defining the distribution type ($\mu = 1$ is parabolic without tails, $\mu \to \infty$ is Gaussian with maximum tails). Simulations were done using fixed rms bunch length and showed that losses in the SPS increase for bunches with large tails (high μ), as seen in Fig. 5. Moreover, the relative improvement in terms of losses thanks to the linearization of the rf voltage is more important for bunches without tails than for bunches with large tails. This is expected since the non-linearity of the rf voltage cannot be fully compensated using only two rf harmonics, especially for particles with large amplitude of oscillation in phase space. Experimentally, the tail population is difficult to evaluate from the bunch profile. The small improvement of losses in the SPS by the linearization of the rf voltage is an indication that the tail population is larger than expected.

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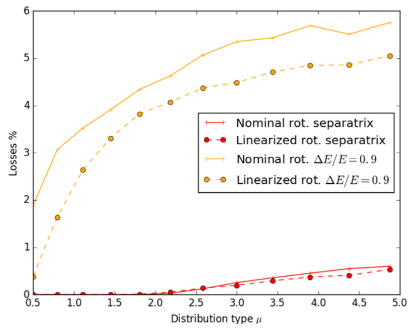

Figure 5: Simulated losses in the SPS with and without linearization of the rf voltage in the PS during bunch rotation (see Fig. 2 for definition of losses). Simulations were performed for bunches with the same rms bunch length (with ε_L = 0.35 eVs) and different distribution type μ.

POST-ACCELERATION AND LONGITUDINAL SHAVING

Several rf manipulations are performed during the cycle in the PS like bunch splitting and controlled emittance blow-up. Several impedance sources can also lead to uncontrolled emittance blow-up which could eventually generate tails in the longitudinal distribution. This is the case for bunch splittings performed at top energy, before the bunch rotation and extraction to the SPS [6].

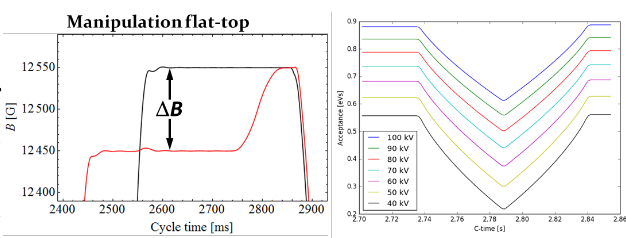

Figure 6: Magnetic field for post-acceleration (left, in red), together with the longitudinal acceptance during post-acceleration for a constant rf voltage (right).

To put in evidence the tail population, the magnetic field program was adjusted to perform the last rf manipulations on an intermediate plateau, followed by a post-acceleration using a 40 MHz cavity as main rf. This program is shown in Fig. 6 (left). The 40 MHz cavities are narrow-band, the post-acceleration was hence performed with fixed rf frequency after synchronization with the SPS signals. The magnetic field increase ΔB was calculated to separate the captured beam from the uncaptured beam by ≈ 16 rf bucket heights, to lose uncaptured beam in the PS instead of the SPS.

The rf voltage at 40 MHz can be set to a constant value to make a dip in the longitudinal acceptance during post-acceleration, as shown in Fig. 6 (right). The rf voltage is then adjusted to shave the tails of the bunch out of the separatrix, without affecting the core. For a longitudinal emittance of ε_L = 0.35 eVs, it is expected that the ideal rf voltage for shaving is 55 kV. Measurements of losses in the SPS were performed using post-acceleration in the PS and different

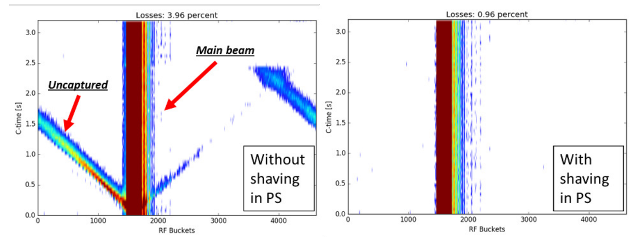

Figure 7: Uncaptured beam in the SPS (rf harmonic h = 4620) measured from the Fast BCT, with and without longitudinal shaving in the PS (rf voltage set to 60 kV during post-acceleration).

rf voltage for shaving, using a beam with nominal intensity but only 36 bunches due to limitation of the energy from the pulsed 40 MHz rf system. An example is shown in Fig. 7. The ideal rf voltage during shaving was found to be 66 kV for results presented in Fig. 8. The total losses of both PS and SPS (in red) as well as the extracted bunch length remain unchanged, while the tails are shaved and lost in the PS and transfer line instead of the SPS. For smaller rf voltage, the core of the bunch is also shaved and the total losses increase. Therefore, the longitudinal tails are present and extend at least up to ε_L = 0.45 eVs, further than the longitudinal emittance of the core of the bunch which is ε_L = 0.35 eVs.

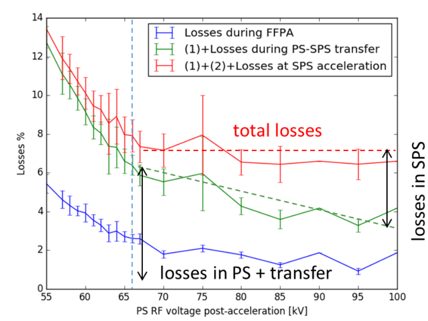

Figure 8: Losses in PS and SPS measured from the DC BCTs, with fixed frequency post-acceleration (FFPA) in the PS and variable rf voltage for longitudinal shaving.

CONCLUSIONS

The linearization of the rf voltage during the first part of the bunch rotation only gave small improvement in terms of losses, indicating that the tail population may be larger than expected. To prove it, post-acceleration was set up to perform longitudinal shaving before bunch rotation, and results give a clear indication that the tail population is large before bunch rotation. Further studies are planned to identify the source of the longitudinal tail generation.

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