STUDIES OF LONGITUDINAL BEAM STABILITY IN CERN PS BOOSTER AFTER UPGRADE

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Abstract

The CERN PS Booster, comprised of four superposed rings, is the first synchrotron in the LHC proton injection chain. In 2021, after major upgrades, the injection and extraction beam energies, as well as the acceleration rate, will be increased. The required beam intensities should be a factor of two higher for nominal LHC and fixed-target beams, and the currently used narrow-band ferrite systems will be replaced by broad-band Finemet cavities in all four rings. Future beam stability was investigated using simulations with the Beam Longitudinal Dynamics (BLonD) code. The simulation results for existing situation were compared with beam measurements and gave a good agreement. An accurate impedance model, together with a careful estimation of the longitudinal space charge, was used in simulations of the future acceleration cycle in single and double RF, with phase and radial loops and controlled longitudinal emittance blow-up. Since the beam is not ultra-relativistic and fills the whole ring (h=1), the front and multi-turn back wakes were taken into account, as well as the RF feedbacks which reduce the effect of the Finemet impedance at the revolution frequency harmonics.

INTRODUCTION

The LHC proton injection chain at CERN will be upgraded by 2021 after Long Shutdown 2 (LS2) [1]. The CERN PS Booster (PSB) is the first synchrotron in the chain; it is comprised of four superposed rings, which currently accelerate protons from 50 MeV to 1.4 GeV kinetic energy. After LS2 the injection and extraction energies will be 160 MeV and 2 GeV respectively both for LHC and some high intensity beams.

At present there are three RF systems, each with one cavity: C02 for acceleration (h=1, V_1 = 8 kV), C04 for bunch shaping (h=2, V_2 = 8 kV) and C16 for controlled emittance blow-up (6<h<16, V_3 = 6 kV). During LS2 these tunable narrow-band ferrite cavities will be replaced by broad-band Finemet ones [2]. The total available peak voltage will be 24 kV distributed across 36 gaps, with 20 kV used in operation to have redundancy. The longitudinal emittance is needed to be blown up from 1 eVs to 3 eVs to reduce space charge at PS injection (currently it rises from 1 eVs to 1.4 eVs for nominal LHC beams).

The longitudinal beam stability after LS2 has been studied using the CERN Beam Longitudinal Dynamics (BLonD) code [3, 4], after comparing simulation results with beam measurements in the current situation.

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MEASURED AND SIMULATED BEAM PARAMETERS

Several measurements have been done for the current situation [5, 6] after a ten cell Finemet prototype cavity was installed in one of the four PSB rings. Here a comparison between simulations and measurements of a bunch accelerated in single RF with the C02 cavity will be shown. Space charge and the full current PSB impedance model (with the contribution of ten short circuited Finemet gaps) were included in simulations.

The PSB ramp starts conventionally at 275 ms and ends at 775 ms after the beginning of the cycle. Since it is impractical to simulate the current injection process (transverse effects difficult to include in a longitudinal code), the comparison was started at 350 ms, after filamentation. The measured profile at that time was used to generate a phase space distribution at equilibrium with space charge, intensity effects and an RF voltage slightly higher than 8 kV. The reason was to create a mismatch at the start of the simulation, leading to the same quadrupole oscillations as observed in measurements. A similar approach, giving a shift in phase to the generated distribution, was used to have the same measured dipole oscillations at 350 ms.

Figure 1 shows the bunch length during ramp in BLonD and measurements. Each of the four parts of measured points in the figure contains values from three different cycle measurements. In fact it is impossible to obtain data relative to the same cycle for the entire ramp with sufficient resolution. In addition there is significant shot-to-shot variation in intensity, bunch position, and length. In overall the agreement is good, even if a smoother bunch length evolution can be seen in simulations (the same applies for dipole oscillations).

AFTER UPGRADE IMPEDANCE MODEL

The value for space charge impedance $|Z_{sc}|/n$ at PSB injection (160 MeV) was carefully estimated dividing the PSB into 211 sections and considering, for each of them, the beam pipe cross section and beam transverse size to evaluate the space charge contribution in that part of the ring. An average of all the 211 sections was then computed [7]. The found value (around 600 Ω) was then rescaled through the ramp with $\beta\gamma^2$, where β and γ are the relativistic parameters.

The future PSB impedance model contains contributions from 36 Finemet gaps, extraction kickers and cables, KSW kicker magnets, resistive wall and beam pipe step transitions [2, 8]. The Finemet amplifiers, through low-level RF feedbacks, will provide a current able to significantly suppress beam loading. The effect will be equivalent to a reduction of the absolute value of the Finemet impedance by

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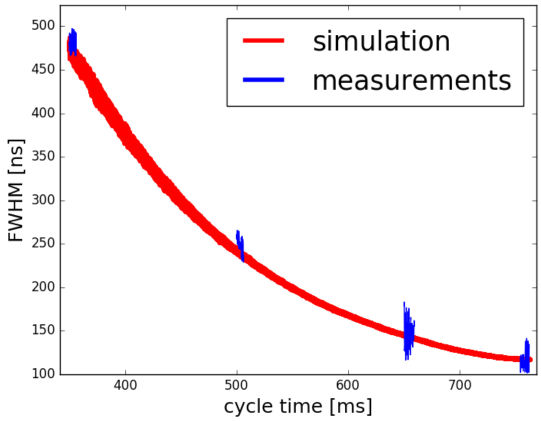

Figure 1: Full-width half-maximum bunch length evolution (50 MeV-1.4 GeV) in simulation and measurements for N=5×10^{12} ppb.

a factor of 60 at the revolution frequency and its multiples up to eight [9]. The phase in correspondence of these reductions is presently not known, therefore the effect of the feedbacks was modelled subtracting resonator impedances from the Finemet impedance, see Fig. 2. This assumption is justified by the fact that the Finemet impedance does not depend on energy, the Hilbert transform links its real and imaginary parts and causality is satisfied with good approximation. The impedance obtained subtracting resonators fulfils the Hilbert transform for linearity and causality is preserved. The affected frequencies are the first eight revolution harmonics (which change during acceleration), the quality factors of the resonators match the width of the measured notches and the shunt impedance is set to the value of the real part of the impedance without reduction. That way the overall impedance has no negative real part, but the reduction is less than the wanted factor 60.

The Finemet impedance without reduction dominates the full model and Fig. 2 shows that the impedance is almost entirely resistive. After feedback reduction (closed-loop), the real part is drastically reduced and what remains is just the capacitive contribution which has roughly $|Z|/n$ constant and opposite in sign to space charge. To see the effect of the notches, a multi-turn wake lasting several hundreds of turns has to be considered in simulations.

Figure 3 shows a typical profile in double RF after injection and the corresponding induced voltage after saturation, with and without impedance reduction.

AFTER UPGRADE SIMULATION RESULTS

It was shown in [10] that intensity effects after LS2 are not negligible in the PSB. In particular, for LHC-type beams, the beam loading due to the resistive part of the impedance of 36 Finemet gaps without feedback reduction reduces the bucket area. The space charge, also important in the PSB, reduces the bucket even further to a point where acceleration in single RF at constant 8 kV would lead to significant particle losses.

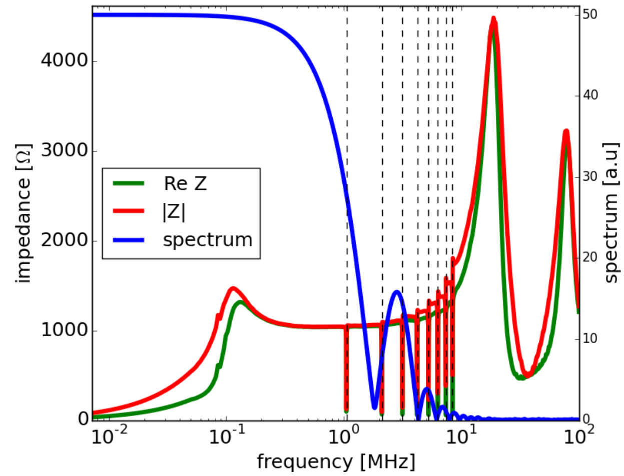

Figure 2: Absolute value and real part of the full PSB impedance model without space charge. The vertical lines indicate the first eight revolution harmonics. The spectrum of a 1 eVs bunch at cycle time 300 ms in bunch lengthening double RF (N = 3.6×10^{12} ppb) is shown.

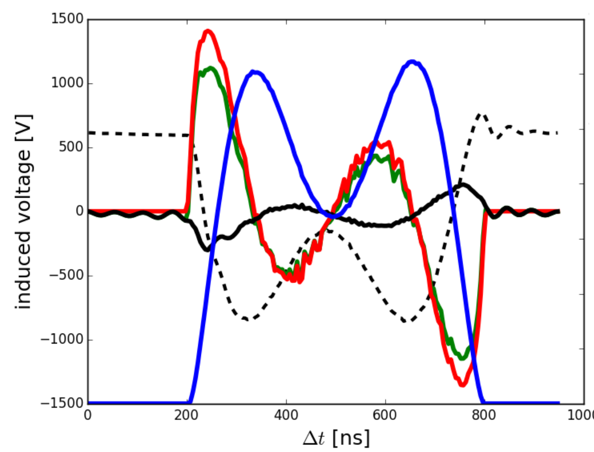

Figure 3: Total induced voltage (green) generated by the bunch described in Fig. 2. The space charge and the closed-loop Finemet contributions are in red and black continuous respectively. The resistive Finemet voltage without reductions (black dashed) is shown for comparison. After saturation of the multi-turn wake, the closed-loop Finemet voltage is capacitive and opposite in sign to space charge. The line density is in blue (V_1 = 10 kV, V_2 = 10 kV).

All the studies presented here are done for the closed-loop operation of the Finemet gaps. Two types of beam were examined, the nominal LHC and a hypothetical high intensity. The following settings (cycle I) are common to both cases. The accelerating harmonic is h=1. The first part of the ramp (from 275 to 350 ms) is done in double RF in bunch lengthening mode to reduce the peak line density and transverse space charge [10, 11], using V_1 = 10 kV and V_2 = 10 kV. With V_1 = V_2 the line density has two peaks of similar height, see Fig. 3. In the interval (350-550) ms V_2 is dropped to zero, while V_1 is increased to 18 kV and

16 kV for LHC and high intensity beams respectively. This difference is due to the fact that the Finemet amplifiers have to provide a part of their available current to reduce beam loading (impedance reduction discussed before), which is higher for bunches with higher current. During (550-650) ms it is planned to increase the initial 1 eVs emittance to 2.6 eVs for high intensity and 3 eVs for LHC beams (in single RF). Band-limited RF noise injected in the phase loop of the h=1 cavity has been used for blow-up [12]. Finally V_1 is dropped to 8 kV (current peak accelerating voltage) in the interval (650-775) ms to have the desired bunch length at extraction for both beams.

High-intensity Beam

In the post-LS2 scenario, all the operational beams for the PS experiments will be extracted at 2 GeV kinetic energy. The highest intensity case with $N = 1.6{\times}10^{13}$ was simulated, first without controlled longitudinal emittance blow-up. An instability leading to unwanted emittance growth and significant dipole and quadrupole oscillations started around 480 ms (a second instability began at 640 ms). Looking at the phase space (Fig. 4), the main frequency components of the induced voltage, and comparing the bunch spectrum with the impedance, it was suspected that the Finemet impedance peak around 20 MHz in Fig. 2 leads to microwave instability as bunch is getting shorter during ramp. Since it should be possible to increase the number of revolution harmonics at which the Finemet impedance is reduced, that number was raised in simulations from 8 to 16 to cover the frequencies up to 20 MHz. That way the start of the instability remained the same, but the second instability was delayed until 700 ms (green and red curves in Fig. 5). For the ramp entirely in single RF with $V_1 = 16$ kV (cycle II), the instability began at 505 ms and 560 ms with impedance reduction up to harmonic 8 and 16 respectively. This indicates that the voltage manipulations done before and after the blow-up also enhance the instability. However the final emittance at 775 ms is smaller for cycle I since an instability starting earlier in the cycle increases the emittance and bunch length providing relatively more stability later in the ramp. Controlled emittance blow-up was also applied, its further optimization is needed to reduce particle losses.

LHC-type Beam

The instability found for high intensity beams was not seen for LHC-type beam with $N = 3.6 \times 10^{12}$ particles. It was possible to smoothly blow up the emittance to the requested 3 eVs in the interval 550-650 ms using all the voltage manipulations described earlier (see [12] for a similar case). The bunch length at extraction was 195-205 ns as required, and there were few losses (<0.007 %) when the voltage was decreased from 18 kV to 8 kV.

CONCLUSION

The PSB longitudinal beam dynamics simulations were done to study beam stability after upgrades. Comparison between measurements and simulations of the present situation was used to gain confidence in simulation results. The reduction of the Finemet impedance through the low-level feedbacks was modelled in BLonD. For the nominal LHC beam stability problems were not observed and the required emittance at extraction was reached through injection of band-limited phase noise in the main cavity. For high-intensity beams an instability was found, a countermeasure could be the increase of the number of revolution harmonics at which the Finemet impedance is reduced. It emerged also that the voltage manipulations assumed in simulations could enhance this instability.

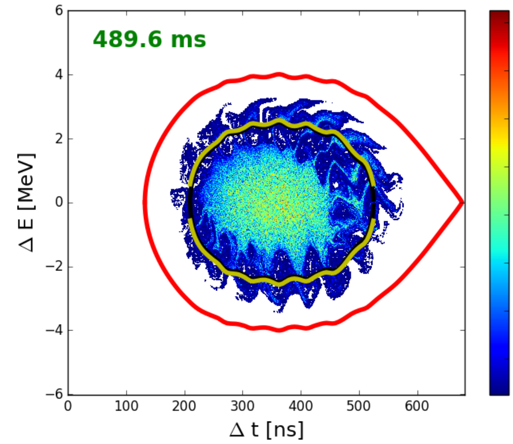

Figure 4: High frequency modulation seen in phase space due to the induced voltage. The separatrix is in red, the yellow curve identifies the trajectory used to compute the emittance measured at 5% of the line density and the color bar indicates the particle density.

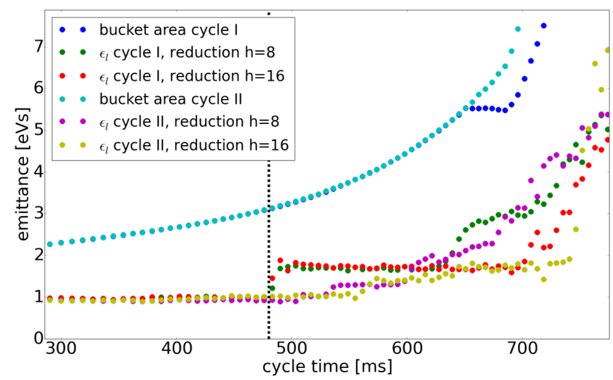

Figure 5: Emittance ϵ_l evolution with and without voltage manipulations for high intensity beams using impedance reduction up to harmonic 8 and 16. Instability after 480 ms causes uncontrolled emittance blow-up.

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