CONTROLLED LONGITUDINAL EMITTANCE BLOW-UP USING BAND-LIMITED PHASE NOISE IN CERN PSB

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Abstract

Controlled longitudinal emittance blow-up (from 1 eVs to 1.4 eVs) for LHC beams in the CERN PS Booster is currently achievied using sinusoidal phase modulation of a dedicated high-harmonic RF system. In 2021, after the LHC injectors upgrade, 3 eVs should be extracted to the PS. Even if the current method may satisfy the new requirements, it relies on low-power level RF improvements. In this paper another method of blow-up was considered, that is the injection of band-limited phase noise in the main RF system (h=1), never tried in PSB but already used in CERN SPS and LHC, under different conditions (longer cycles). This technique, which lowers the peak line density and therefore the impact of intensity effects in the PSB and the PS, can also be complementary to the present method. The longitudinal space charge, dominant in the PSB, causes significant synchrotron frequency shifts with intensity, and its effect should be taken into account. Another complication arises from the interaction of the phase loop with the injected noise, since both act on the RF phase. All these elements were studied in simulations of the PSB cycle with the BLonD code, and the required blow-up was achieved.

INTRODUCTION

In 2021, after Long Shutdown 2 (LS2), all the LHC injectors will be upgraded to fulfil the specifications of the LIU (LHC Injectors Upgrade) project [1].

The CERN PS Booster is the first synchrotron in the LHC proton injection chain. Currently it accelerates protons from 50 MeV to 1.4 GeV kinetic energy E_k in about 500 ms, while the longitudinal emittance is increased from 1 eVs to 1.4 eVs in a controlled way to provide stability of the beam during the ramp and to reduce space charge effects at PS injection. After LS2, the new injection and extraction energies will be 160 MeV and 2 GeV respectively, but the cycle duration will not change. The beam intensity will be a factor of two higher than now and the emittance needs to be increased from 1 eVs to 3 eVs.

Three RF systems are used in the PSB, one for acceleration (C02, h=1, V_1 = 8 kV), one for bunch shaping (C04, h=2, V_2 = 8 kV), and one for controlled longitudinal emittance blow-up (C16, h>6, V_3 = 6 kV). All these narrow-band and tunable ferrite RF systems will be replaced by a broad-band Finemet system [2], to allow for higher peak voltages and flexibility. The Finemet gaps will be modular, each of them will be set to the needed harmonic and peak voltage, for a total of 24 kV available.

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Simulations studies have shown that the required emittance blow-up can be achieved using an optimised phase modulation of the C16 RF system [3]. This paper will deal with a possible alternative to this technique, namely the injection of band-limited RF noise in the main RF harmonic cavity. Bunch shaping and blow-up using band-limited noise have already been studied [4]. Longitudinal emittance blow-up using phase noise, never tried in the PSB, is successfully implemented in CERN SPS and LHC [5, 6], where there are no dedicated RF systems for blow-up and cycles are longer.

There are three main reasons to propose an alternative to the current method of blow-up. The RF phases between the different PSB RF systems are not accurately known in operation and there can be issues of reproducibility. In addition, the present method for blow-up implies the use of a dedicated RF system that can be removed with noise injection in main RF system. Finally, the proposed technique, in addition to blow-up, is able to lower the peak line density of the bunch decreasing the impact of intensity effects.

The phase noise can be injected through phase loop at a limited sampling rate. Simulations using the CERN BLonD code [7] with a corresponding longitudinal impedance model have been used to verify the feasibility of this method in upgraded PSB (after LS2).

THE BAND-LIMITED PHASE NOISE

The effect of band-limited phase noise lies in-between the diffusion generated by white phase noise acting on all frequencies and the resonant excitation created by sinusoidal phase modulation. Indeed only the particles with a synchrotron frequency inside a certain band are affected (see Fig. 1). The band upper limit f_{up} is above the bunch central synchrotron frequency f_s (with intensity effects) to affect fully the bunch core and its lower limit f_{down} is related to the target bunch length (or emittance) to be reached. Figure 1 shows also that space charge, defocusing in the PSB (below transition), lowers the zero-intensity synchrotron frequency f_{s0} and the noise band should follow this shift.

The RF phase noise $\phi(t)$ was constructed similarly to the LHC implementation. It was obtained colouring white phase noise in frequency domain with the desired probability density and Fourier-transforming the result to time domain [8]. The double-sided noise power spectral density $S(f)$ [rad^2/Hz] (see Fig. 2) determines the rms phase noise as $\phi_{rms} = \sqrt{f_0 < S(f) >}$ (f_0 is the revolution frequency).

SIMULATIONS IN SINGLE RF

The effect of band-limited phase noise on emittance blow-up during acceleration ramp was simulated using the BLonD

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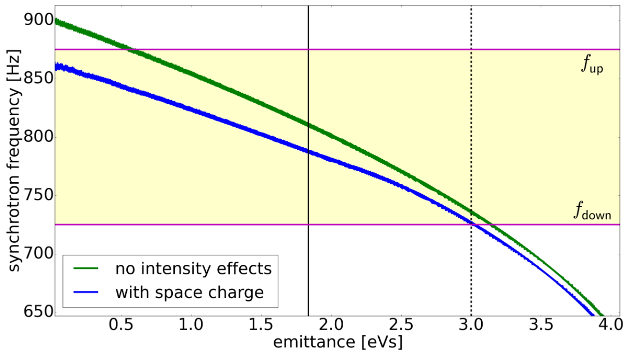

Figure 1: Synchrotron frequency distribution in single RF calculated with (blue line) and without (green line) space charge effect (N = 3.6×10^{12} ppb) in PSB at E_k = 1 GeV. The bunch emittance increases from 1.8 eVs to 3 eVs applying phase noise in the band [725 Hz, 875 Hz] (magenta lines).

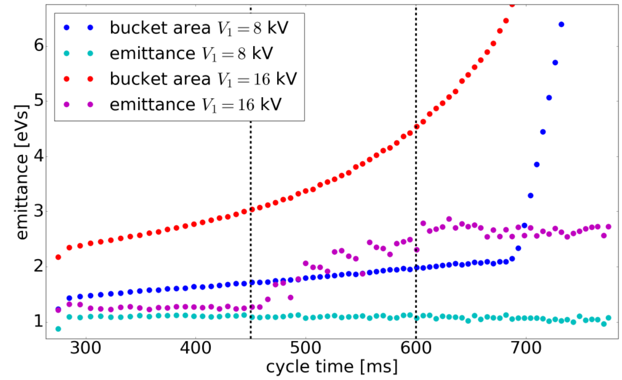

Figure 3: Emittance blow-up using V_1 = 16 kV. Small time margin with V_1 = 8 kV. The PSB injection and extraction times are at 275 ms and 775 ms. The bunch length (emittance) is measured at 5% of the line density.

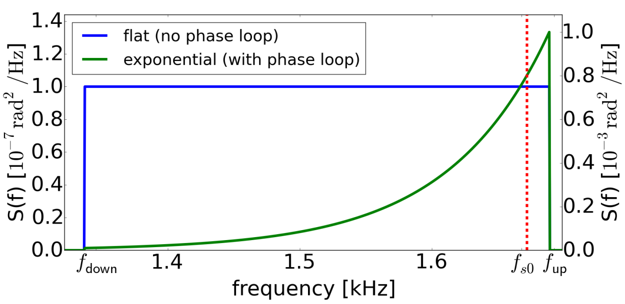

Figure 2: Flat (left axis) and exponential (right axis) spectral densities used in simulations without and with phase loop respectively at E_k = 425 MeV (start of blow-up).

code [7]. The longitudinal space charge was carefully estimated at injection energy and then rescaled through the cycle with $\beta\gamma^2$, where β and γ are the relativistic parameters. The full PSB impedance model, consisting of 36 Finemet gaps, extraction kickers and cables, KSW kicker magnets, resistive wall and beam pipe step transitions, was included in simulations [2, 9]. The Finemet resistive impedance is reduced by RF feedback. The effect of the feedback is included in simulations (as opposed to results presented in [10]) using two different models. The first consists in subtracting resonator impedances from the Finemet impedance at the revolution harmonics [11] to reproduce the measured notches (36 dB reduction), the second reduces the whole Finemet impedance at all frequencies by 11 dB (this value gives similar results for bunch stability during ramp). In the first case the values of f_s during blow-up are slightly higher (the resonators increase the total capacitive impedance), but the same parameters for blow-up were suitable in both cases.

The simulations were done for constant 8 kV and 16 kV voltages at h=1 with a realistic momentum program [12]. The 8 kV case shows no losses, but there is little time for a smooth blow-up. With 16 kV it was possible to increase the emittance up to the requested value of 3 eVs (Fig. 3).

The noise was generated at regular intervals to follow the changes of the synchrotron and revolution frequencies during the blow-up interval (450-600) ms (f_{s0} decreases from 1.7 kHz to 0.9 kHz while f_0 increases from 1.4 MHz to 1.65 MHz). Indeed, since f_0 and f_{s0} vary significantly along the PSB cycle, ideally the noise should be often regenerated to follow these changes. On the other hand if the regeneration is done too often, then the resolution in frequency domain is too low and $S(f)$ will cover a band different than the chosen one. A good compromise was found regenerating the noise sample every 10000 turns.

The spectral density $S(f)$ was chosen constant in the band [0.8 f_{s0}, f_{s0}]. Indeed, for the examined intensity (LHC beams, N = 3.6×10^{12} ppb), choosing $f_{\mathrm{up}} = f_{s0}$ allows to affect fully the bunch core since $f_s < f_{s0}$ during blow-up. The value $f_{\mathrm{down}} = 0.8 f_{s0}$ was chosen examining the synchrotron frequency distribution with intensity effects during the blow-up time interval for the emittance increase from 2 eVs to 3 eVs. Then the noise amplitude at 450 ms, rescaled with f_{s0} during the blow-up to have the same noise strength ϕ_{rms}, was gradually risen to a value leading to the required emittance at 600 ms (S = 10^{-7}rad^2/Hz, Fig. 2).

Figure 4 shows that intensity effects help for particle filamentation in phase space during and after controlled emittance blow-up with phase noise which produces islands in phase space modulating the bunch profile at PSB extraction.

EFFECT OF PHASE AND RADIAL LOOPS

In the simulations shown above, it was assumed that the noise is injected turn after turn directly in the main RF cavity. However, the operational scenario is that the noise will be introduced in the beam phase loop. This causes two complications. Firstly, the noise will be counteracted by phase loop. Additionally, the noise signal will only be sampled every 10 μs, the interval between two consecutive phase loop triggers [13]. This should not cause any issue since the sampling frequency of 100 kHz is well above the range of synchrotron frequencies 0.9-1.7 kHz during the blow-up.

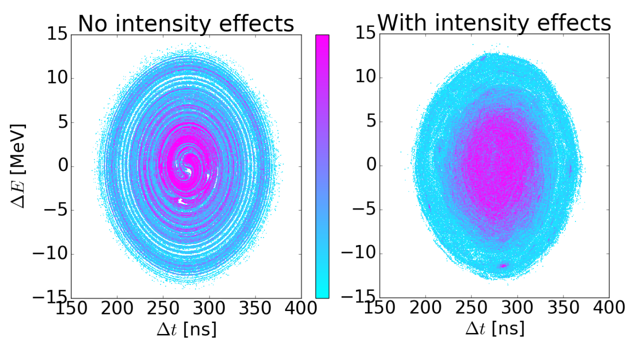

Figure 4: Bunch in longitudinal phase space after emittance blow-up at PSB extraction without intensity effects and with the full impedance model (Finemet impedance reduction with notches). The colour bar indicates the particles density.

The main goal of the phase loop is to damp the rigid-bunch dipole oscillations. This is usually done measuring at turn n the difference between the beam and designed synchronous phases $\Delta\phi$ and changing accordingly the RF frequency ω_{RF} by $\Delta\omega_{PL}$ at turn n+1. This passage from $\Delta\phi$ to $\Delta\omega$ is done since phase measurements could contain unwanted high frequency components that are filtered in this integration.

This frequency shift leads also to a change of the bunch orbit radius R from the design machine radius R_d. The aim of the radial loop is to maintain the orbit at the design one in the long run, reducing $|\Delta R| = |R - R_d|$. This is done giving a second contribution $\Delta\omega_{RL}$ to ω_{RF}. Thus, for each turn, $\Delta\omega_{RF} = \Delta\omega_{PL} + \Delta\omega_{RL}$, where the two contributions have usually opposite signs and $|\omega_{PL}| > |\omega_{RL}|$.

If the phase noise is introduced in the phase loop (as in the PSB), then its contribution will be summed to $\Delta\phi$. The usually flat band-limited spectrum will then have a notch close to f_{s0} that can slow down the diffusion of the core. A compensation for this effect can be adopted changing the shape of the spectrum, as for PSB, where an exponentially growing $S(f)$ in the band $[f_{\text{down}}, f_{\text{up}}]$ was chosen (Fig. 2).

The phase loop in the PSB is characterized by a Cascaded integrator-comb (CIC) filter [13] which yields

$$\Delta\omega_{PL}^{n+1} = a_1\Delta\omega_{PL}^{n} + g_{PL}(b_0\Delta\phi^n - b_1\Delta\phi^{n-1}), \qquad (1)$$

where $g_{PL} > 0$ is the gain and b_0, b_1 and a_1 are constants $\lesssim 1$. The value of g_{PL} has to be lower than f_0 to have a stable phase loop.

The relative error $\Delta R/R_d$ in the radial loop is filtered with a PI (Proportional-Integrator) corrector [13], and

$$\Delta\omega_{RL}^{n+1} = \Delta\omega_{RL}^{n} + (g_P + g_I)\left(\frac{\Delta R}{R_d}\right)^n - g_P\left(\frac{\Delta R}{R_d}\right)^{n-1}, \qquad (2)$$

where g_P and g_I are positive gains. In reality ΔR is measured through transverse pick-ups in PSB. In simulations, ΔR was estimated assuming a constant magnetic field for all particles at a given turn

$$\frac{\Delta R}{R_d} = \frac{\Delta\omega_{RF}}{\omega_{d,RF}}\frac{\gamma^2}{\gamma_T^2 - \gamma^2}, \qquad (3)$$

$\omega_{d,RF}$ and γ_T being the design RF frequency and the relativistic factor at transition respectively.

Starting from a 1 eVs bunch it was possible to blow up the emittance to 3 eVs increasing by four orders of magnitude the amplitude of the noise in f_{s0} compared to the case without loops, see Fig. 2. The emittance evolution was similar to Fig. 3. The phase and radial loop gains ($g_{PL} = 330$ 1/s, $g_P = 10^7$ rad/s, $g_I = 10^6$ rad/s) were chosen in such a way that $\Delta\omega_{PL}$ and $\Delta\omega_{RL}$ had a stable evolution during and after the blow-up interval (Fig. 5).

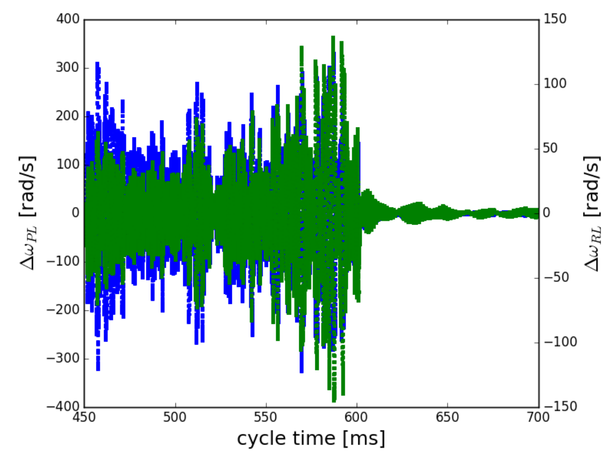

Figure 5: $\Delta\omega_{PL}$ (blue, left axis) and $\Delta\omega_{RL}$ (green, right axis) evolution during cycle time 450-700 ms. There is no injected noise after 600 ms, the loops are always on.

This simulation showed that the phase noise could be applied together with the phase loop and that the 10 μs sampling rate should not be an issue.

CONCLUSION

These studies have shown that bunch excitation with band-limited phase noise in the main RF system can provide significant controlled longitudinal emittance blow-up in a fast-cycling machine with strong space charge like the CERN PSB. For an optimised set of parameters it was possible to increase by factor 3 the emittance applying the noise only for 150 ms during the ramp. The requested blow-up was also achieved injecting the noise through the phase loop with limited sampling rate. This method, which could replace the currently used one based on phase modulation in a dedicated high harmonic RF system, will be tested in PSB in 2017 after minor low-level RF modifications.

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REFERENCES

[1] "LIU Technical Design Report - Volume I: Protons", edited by M. Meddahi and others, CERN-ACC-2014-0337, 2014.

[2] M. M. Paoluzzi et al., "Design of the New Wideband RF System for the CERN PS Booster," IPAC2016, Busan (Korea), 2016.

[3] S. Albright, private communications, CERN, 2017.

[4] T. Toyama, "Uniform Bunch Formation by RF Voltage Modulation with a Band-Limited White Signal," NIM A, 447, 317–327, 2000.

[5] G. Papotti et al., "Study of Controlled Longitudinal Emittance Blow-Up for High Intensity LHC Beams in the CERN SPS," EPAC2008, Genoa (Italy), 2008.

[6] P. Baudrenghien et al., "Longitudinal Emittance Blow-Up in the LHC," IPAC2011, San Sebastian (Spain), 2011.

[7] CERN BLonD code, `https://blond.web.cern.ch/`

[8] J. Tückmantel, "Digital Generation of Noise-Signals with Arbitrary Constant or Time-Varying Spectra," EPAC2008, Genoa (Italy), 2008.

[9] C. Zannini, private communications, CERN, 2014.

[10] D. Quartullo, S. Albright and E. Shaposhnikova, "CERN PS Booster Longitudinal Dynamics Simulations for the Post-LS2 Scenario," Proc. ICFA HB2016, Malmö (Sweden), 2016.

[11] D. Quartullo, S. Albright and E. Shaposhnikova, "Studies of Longitudinal Beam Stability in CERN PS Booster After Upgrade," IPAC2017, Copenhagen (Denmark), 2017.

[12] S. Albright, "PSB Magnetic Cycles to 1.4 and 2 GeV After LS2," CERN EDMS, to be published.

[13] M. E. Angoletta, "PS Booster Beam Tests of the New Digital Beam Control System for LEIR," CERN, AB-Note-2005-017-RF.