CERN PS BOOSTER LONGITUDINAL DYNAMICS SIMULATIONS FOR THE POST-LS2 SCENARIO

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Abstract

The CERN PS Booster is the first synchrotron in the LHC proton injection chain, it currently accelerates particles from 50 MeV to 1.4 GeV kinetic energy. Several upgrades foreseen by the LHC Injectors Upgrade Program will allow the beam to be accelerated from 160 MeV to 2 GeV after Long Shutdown 2 in 2021. The present RF systems will be replaced by a new one, based on Finemet technology. These and other improvements will help to increase the LHC luminosity by a factor of ten. In order to study beam stability in the longitudinal plane simulations have been performed with the CERN BLonD code, using an accurate longitudinal impedance model and a reliable estimation of the longitudinal space charge. Particular attention has been dedicated to the three main features that currently let the beam go stably through the ramp: Double RF operation in bunch-lengthening mode to reduce the transverse space charge tune spread, exploitation of feedback loops to damp dipole oscillations, and controlled longitudinal emittance blow-up. RF phase noise injection has been considered to study if it could complement or substitute the currently used method based on sinusoidal phase modulation.

INTRODUCTION

In 2021, after Long Shutdown 2 (LS2), all the injectors of the LHC will be upgraded according to the LHC Injectors Upgrade (LIU) program [1]. These improvements will contribute to an increase of the LHC luminosity by a factor of ten, meeting the expectations of the HL-LHC project.

CERN's PS Booster (PSB) is the first synchrotron in the LHC proton injection chain, it currently receives particles from the linear accelerator Linac2 at 50 MeV kinetic energy and accelerates them up to 1.4 GeV before extraction to the Proton Syncrotron (PS). In the post LS2 scenario, following the specifics of the LIU PSB program, Linac2 will be replaced by the new Linac4 and the injection energy will be increased to 160 MeV, in addition nominal LHC-type beams will be extracted at 2 GeV.

The PSB currently has three RF systems. Acceleration is done at h=1, while the h=2 system is used at injection and during the ramp in bunch lengthening mode to reduce the peak line density and minimize the transverse space charge tune spread. A high harmonic cavity (h<=16) is used to blow up the longitudinal emittance of the beam in a controlled way, since high emittance bunches are needed in the PSB for stability and in the PS for space charge reduction before bunch splitting at flat bottom. In the post-LS2 scenario these three RF systems will be replaced by wide-band Finemet loaded cavities [2], which will be modular and will allow multi-harmonic operation. All the functionalities given by the current systems will be supplied by the new system as well.

In a future scenario where a lot of beam parameters will change, and where the momentum program and some impedance contributions (of RF systems and other ring components) will be different, it is vital to predict possible instabilities, which may lead to particle losses and deterioration of beam quality during the ramp and at extraction.

The most reasonable tool for this is reliable multi-particle longitudinal tracking, and the CERN BLonD code [3] has been adapted for this purpose. BLonD was conceived in 2014 and has been used extensively to simulate longitudinal dynamics of the various CERN rings (LEIR, PSB, PS, SPS and LHC) for both ions and protons. Several features are included: Acceleration, multiple RF systems, collective effects, multibunch operation, low level RF feedbacks, phase modulation or phase noise injection for controlled longitudinal emittance blow-up.

This paper describes features of the BLonD code together with obtained results. We start with an explanation of how the induced voltage is derived turn by turn, show how to numerically calculate an accurate phase shift program in double RF bunch-lengthening mode with a voltage ratio of 3/4 (currently used for LHC beams) with intensity effects and then we will briefly present the low level RF feedbacks used in the PSB and a result from their implementation in BLonD. Finally the theory behind controlled longitudinal emittance blow-up with RF phase noise injection will be introduced and the corresponding algorithm in the code will be explained. RF phase noise has never been tested in the PSB but simulations can reveal its usability in this particular case.

INDUCED VOLTAGE CALCULATION

Longitudinal Space Charge and Impedance Model

The longitudinal space charge effect is significant in non-relativistic machines so an accurate calculation of its contribution is very important. Let's call Z_{sc} the purely imaginary space charge impedance and $\lambda(t)$ the longitudinal bunch profile such that $\int_T dt\lambda(t) = N$, where N stands for the beam intensity; here t is the time longitudinal coordinate and $T = [0, T_{rev}]$ is the one-turn time interval. The space charge induced voltage can be calculated with good approximation using

$$V_{sc}(t) = \frac{e}{\omega_{rev}} \frac{|Z_{sc}|}{n} \frac{d}{dt}\lambda(t), \tag{1}$$

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ISBN 978-3-95450-178-6

where e is the proton charge, $\omega_{rev} = 2\pi f_{rev}$ is the design angular revolution frequency and $n = f/f_{rev}$, and f is a generic positive frequency value. Equation (1) shows that the problem of calculating the space charge induced voltage reduces to find the $|Z_{sc}|/n$ value for each beam energy through the ramp. The first point of this curve has been carefully estimated dividing the PSB into 211 sections and, for each of them, taking into account the beam pipe cross section and beam transverse standard deviation to estimate the space charge contribution in that portion of the ring. Finally an average on all the 211 sections was calculated [4]. The $|Z_{sc}|/n$ value found at 160 MeV (603 Ω) was then rescaled through the ramp with $\beta\gamma^2$ (85 Ω at 2 GeV).

The PSB impedance model contains contributions from 36 Finemet gaps, extraction kickers and cables, KSW kicker magnets, resistive wall and beam pipe step transitions [2, 5]. Figures 1 and 2 show the sum of all contributions at injection and extraction energy, for completeness Figure 2 takes into account the longitudinal space charge impedance. The 100 MHz limit derives from measurements and the visible notches in the plots correspond to Finemet impedance reduction at revolution frequency and its multiples up to 8 due to the action of Low Level electronics. We can see that the real part of the Finemet impedance without reduction dominates all the other components while the Finemet imaginary part is prevalent below 1 MHz and dominated by the space charge impedance above that frequency, mostly at low energies.

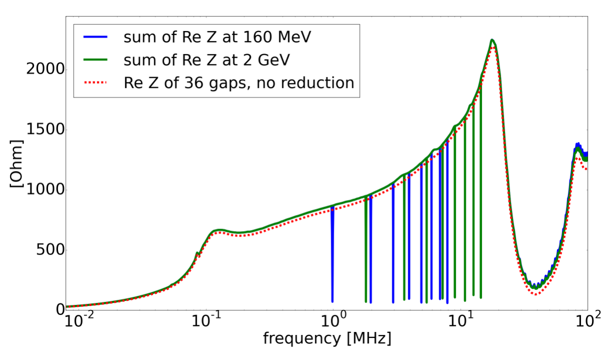

Figure 1: Sum of all the real parts of the impedances at 160 MeV and 2 GeV.

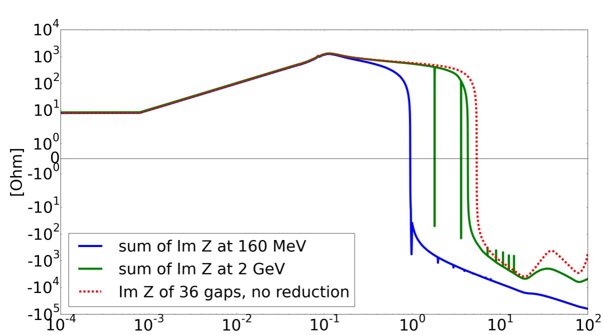

Figure 2: Sum of all the imaginary parts of the impedances at 160 MeV and 2 GeV.

Multi-turn Wake

The space charge induced voltage defined in Eq. (1) cannot be multi-turn in opposition to the one derived from the other PSB impedances that can be calculated numerically as:

$$V_{ind}(t) = -2ef_{max}IDFT(DFT(\lambda) \times Z), \qquad (2)$$

where the discrete Fourier transform and its inverse automatically suppose the signal is periodic in time domain, $f_{max} = 1/(2\Delta t)$ is the maximum frequency that one is interested in with Δt being the sample interval in time domain.

In an ideal case, without acceleration and with stationary line density, it would be reasonable to consider the profile as being periodic on the ring. The period would be T_{rev} and consequently only the points corresponding to f_{rev} and multiples would be considered when the spectrum is multiplied by the impedance in Eq. (2). In the PSB case, where the revolution period approximatively halves from injection to extraction, and the line density varies considerably along the ramp, it is instead more correct to consider an extended period for the profile, meaning that the signal is padded with zeros before performing the Fourier transform and consequently the impedance curve in frequency domain is resolved in detail. In addition, simulations show that even in the idealistic case without zero padding, the induced voltage does not decay in one turn, and so padding zeros is necessary in any case to correctly simulate intensity effects, see Fig. 3. Here and later the PSB convention for the cycle time is used, with injection at 275 ms (C275) and extraction at 775 ms (C775).

It would be ideal to calculate the induced voltage for a certain turn, save its continuation into memory for the next turns, track the particles, apply the saved voltage and so on. One problem is that, because of acceleration, T_{rev} varies and calculating the multi-turn wake in time domain would be computationally expensive since for every sum of two contributions, one from the past and the other from the present, an interpolation is needed. We therefore operate in frequency domain using the fact that a shift of the induced voltage in time domain corresponds to a multiplication by a complex exponential in frequency domain. As a consequence we were able to replace interpolations with multiplications and sums.

Finally we should mention the front wake. In a non-relativistic machine, such as the PSB, the bunch produces a front wake. Operating an inverse Fourier transform on the total impedance of our model the front wake is clearly visible. The one decaying in one turn is, by definition of circular convolution, already taken into account in simulations. However, the one decaying after one turn, although not negligible and comparable to the wake behind, has not yet been included in BLonD. The problem is not trivial since one should go back and forth between two or more consecutive turns to find the correct induced voltages to save into memory.

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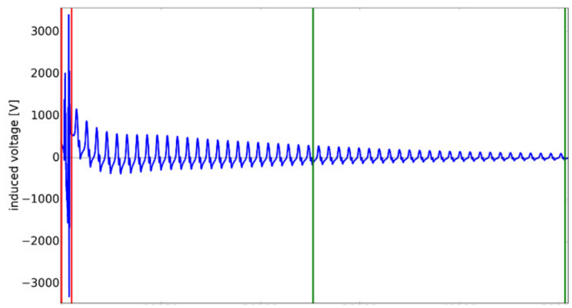

Figure 3: Multi-turn induced voltage at C285: the bunch sits between the red vertical lines while the green lines mark $25T_{rev}$ and $50T_{rev}$. Realistic simulation with intensity of 3.6×10^{12} and complete PSB impedance model.

DOUBLE RF OPERATION WITH INTENSITY EFFECTS

In the PSB the voltage of the h=2 RF system is currently summed to the accelerating voltage in anti-phase or bunch lengthening mode. This method is used to reduce the peak line density and increase the bunching factor, reducing transverse space charge. Constant peak voltages V_1 = 8 kV and V_2 = 6 kV are chosen for nominal LHC beams and the same configuration will likely be used in the post-LS2 scenario [6]. Figure 4 shows in simulation a typical profile related to this cavity setting, where the relative phase between the two RF systems is calibrated in such a way that the two peaks have the same height.

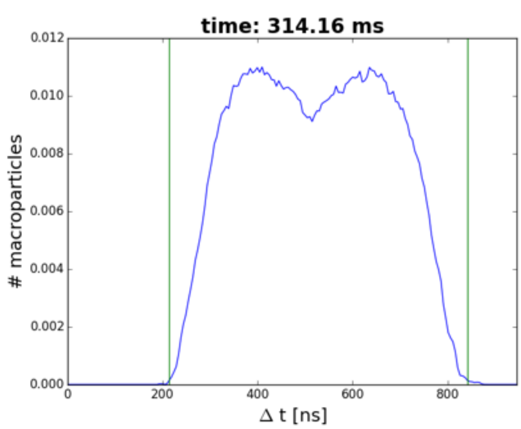

Figure 4: Example of profile using V_1 = 8 kV and V_1 = 6 kV in bunch lengthening mode.

In operation the correct phase for bunch lengthening is found empirically through beam measurements at different points during the ramp and a linear interpolation is used for intermediate points. Because of hardware reasons an additional complication is that the phase shift programmed does not correspond to the true value, therefore they cannot be used in simulations. It is essential to find a method to numerically calculate the correct phase shift if we want to reproduce the double RF dynamics in simulations.

In the following equation let $\Delta\phi_{12}$ be the relative phase between the two RF systems:

$$V_{rf}(\phi) = V_1 \sin(\phi) + V_2 \sin(2\phi + \Delta\phi_{12}) \qquad (3)$$

Without acceleration and intensity effects $\Delta\phi_{12} = \pi$ is the solution to our problem. With acceleration if ϕ_s is close to 0 the phase shift $\Delta\phi_{12} = \pi - 2\phi_s$ is a solution, where ϕ_s is the synchronous phase in single harmonic. Because of the strong acceleration during the second part of the PSB ramp this solution is not accurate, if we add intensity effects the discrepancy is worse.

An algorithm has been developed in BLonD to numerically calculate $\Delta\phi_{12}$, compensating for high ϕ_s and intensity effects. The idea of the algorithm is to integrate the total voltage to obtain the total potential and then numerically find $\Delta\phi_{12}$ in such a way that the two minima have the same depth, see Fig. 5. This procedure is done turn by turn while tracking, so that the phase found for turn n is used as the initial value inside the minimization algorithm for turn n+1. The result is that a potential with minima having the same depth leads to profiles with two peaks at the same height.

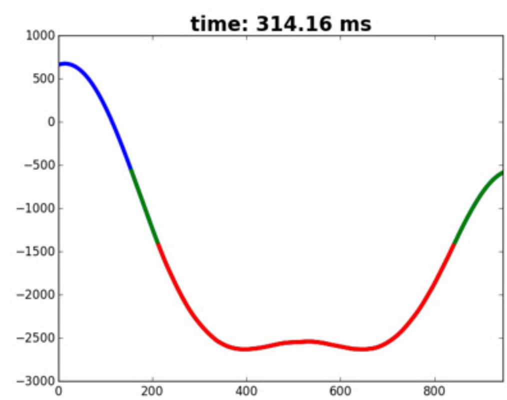

Figure 5: Example of total potential having the desired shape.

We obtained excellent results using this algorithm. Figure 6 shows the profile density evolution of a realistic simulation with intensity N=3.6×10^{12} and longitudinal emittance ϵ = 1.1 eVs.

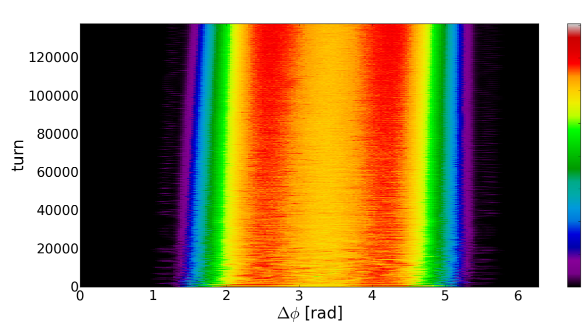

Figure 6: Density plot of the evolution of the bunch profile, from injection to time C400: the red stripes correspond to the two equal peaks.

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Finally Fig. 7 shows the relative phase program used for that simulation (in red) together with the phase program without considering the multi-turn wake (in yellow). The difference is significant and shows the importance of memorizing the induced voltage for the following turns. For completeness the image shows the inaccurate solution $\Delta\phi_{1,2} = \pi - 2\phi_s$ as well (in blue) and the correct phase program in absence of intensity effects (in green).

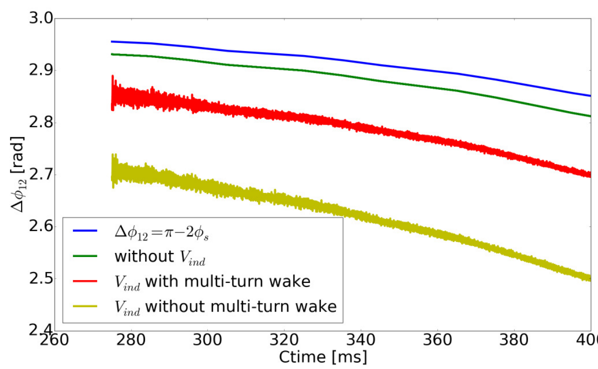

Figure 7: Phase shift programs between the two RF systems from injection to time C400.

PHASE AND RADIAL LOOPS

Phase and radial loops are fundamental to PSB operation, and it is impossible to smoothly accelerate high intensity beams without them. The phase loop is intended to shift the bucket onto the bunch trying to match the two of them, while the radial loop tries to keep the beam centred on the design orbit. The main result is to damp dipole oscillations of the beam.

This feedback mechanism has been implemeted in BLonD and tested on a realistic simulation for the post-LS2 scenario. We simulated a bunch with 0.37 eVs emittance in single RF with peak voltage V = 16 kV from C275 to C350. The collective effects were included with an intensity of 3.6×10^{12} protons. The small emittance and high peak voltage were chosen to have strong dipole oscillations in the absence of loops, see Fig. 8, the feedback routines significantly damp those oscillations.

RF PHASE NOISE FOR BLOW-UP

One of the requirements of LIU for the post LS2 scenario is to increase the longitudinal emittance to 3 eVs during the ramp, from an initial 1.4 eVs (this value is not definitive). With the present ramp, that is from 50 MeV to 1.4 GeV, an emittance of 1.4 eVs is currently achieved starting from 1 eVs using sinusoidal phase modulation of a high harmonic RF system. A separate cavity called C16, with high harmonic number h<=16, creates resonance islands inside the bunch, causing emittance blow up. While preliminary experiments and simulations show that the method based on phase modulation will be able to blow up the beam to the desired 3 eVs in the future, here we propose another approach

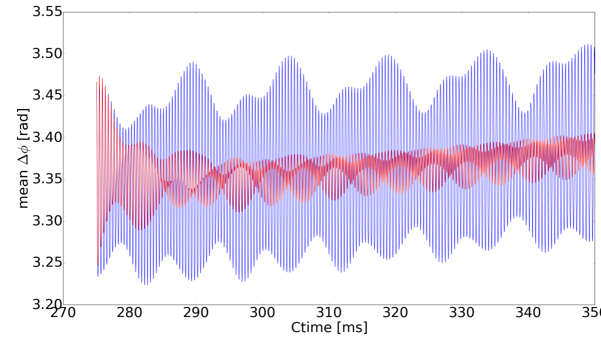

Figure 8: Dipole oscillations of the bunch from C275 to C350 with phase and radial loops on (red trace) and off (blue trace).

to increase the longitudinal emittance in a controlled way, with phase noise injection in the h=1 cavity. This method is currently used in CERN SPS and LHC [7] in the absence of dedicated high harmonic RF system. It has never been tested in the PSB, therefore simulations are a first step to understand if phase noise injection can be a valid alternative, or complement, to phase modulation.

The idea behind phase noise injection is simple. If we inject phase noise with a limited frequency band into a cavity, then all the particles inside the bunch having a synchrotron frequency inside that band will be excited and the amplitude of their oscillations will increase. Figure 9 explains the concept with an example. The red and green curves represent the synchrotron frequency distribution in single RF calculated in two different ways: The first tracks numerically macro-particles and counts how many times a certain particle crosses the axis dE = 0 in one second, the other calculates $f_s = dH/d\epsilon$ where $H(\Delta t)$ is the Hamiltonian passing through the point $(\Delta t, 0)$ and $\epsilon(\Delta t)$ is the area enclosed by it, that is the emittance (in blue). The yellow and black pairs of vertical lines define the bunch position according to two different conventions: The first pair derives from applying the foot tangent method to the bunch profile (PSB LIU current convention), the second discarding all the slices having fewer macro-particles than 5% of the profile peak. The two horizontal lines define the value of the bunch emittance according to the two conventions (around 1.2-1.3 eVs in the example) while the four dashed lines correspond to the frequency of the synchronous particle f_{s0} together with 0.9 f_{s0}, 0.8 f_{s0} and 0.7 f_{s0}. This plot shows for example that if we want to reach an emittance of 2 eVs we should apply a noise with band $[0.7 f_{s0}, f_{s0}]$.

In simulation the noise is generated in the following way taking the LHC implementation as an example. We generate white noise in time domain sampling a standard normal distribution a finite number of times. By definition, its spectrum is flat along all the frequencies. The next step is to multiply it in frequency domain with our band limited spectrum S (usually constant inside the band and zero outside), obtaining the noise probability density $dPf = DFT(N) \times \sqrt{2 f_{max} S}$;

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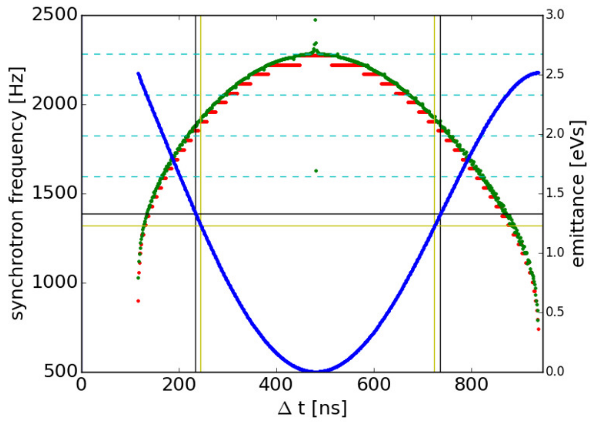

Figure 9: Example of synchrotron frequency distribution in single RF during acceleration; the emittance curve is in blue while the vertical lines define where the bunch position.

here $f_{max} = f_{rev}/2 = 1/(2T_{rev})$. Finally the desired phase noise in time domain is obtained calculating $IDFT(dPf)$.

All the simulations were done in single RF using the same momentum program. We made a first study choosing a constant peak voltage of 8 kV, this value is also currently used to accelerate the beam with the main harmonic C02 ferrite cavity. Figure 10 shows the bunch emittance along the cycle using the vertical cut convention discussed above. Starting from a realistic distribution from Linac4 having $\epsilon = 1.2$ eVs at injection time, the bunch loses 20 % of its particles in the interval [C600, C700]. From the plot we can see that the bucket area is not sufficient, even in an idealistic case without intensity effects (red curve) we would have little time to smoothly blow up the beam.

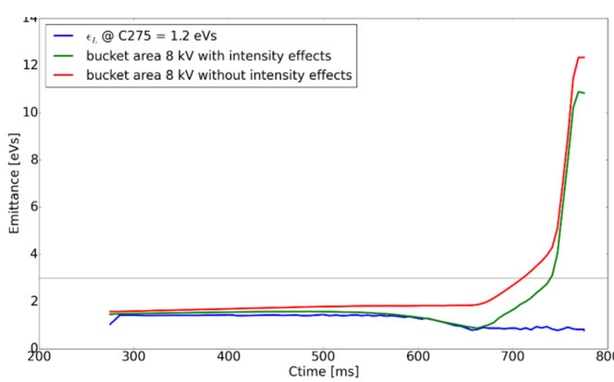

Figure 10: Emittance evolution with constant 8 kV (blue curve). Unacceptable number of losses in the second part of the ramp where the bucket area is not sufficient (green curve); the horizontal line is placed at 3 eVs to show the target.

We then examined the constant 16 kV peak voltage case, knowing that the Finemet cavities will be able to supply up to 24 kV. The result was quite different, enough time for blow up and sufficient bucket area made it possible to reach the target value of 3 eVs by injecting noise during the interval [C450, C600], see Fig. 11. The band of the spectrum was chosen as [0.8 f_{s0}, 1.1 f_{s0}], the lower margin was decided looking at the synchrotron frequency distributions between C450 and C600 and realising that the targeted emittance choosing 0.8 f_{s0} increased from 2 eVs to 3 eVs in that time interval, then we gradually rose the noise amplitude to a value leading to the desired blow up. Since f_{s0} decreases from about 1.75 kHz to 1 kHz in the interval [C450, C600], the phase noise was regenerated every 5000 turns to be able to follow the change. In addition, at every noise update, the amplitude of the spectrum was rescaled with f_{s0} to obtain the same noise strength $\sigma_{\phi_{noise}}$ during this time interval.

The profile at extraction had a bunch length lower than 205 ns, a $\delta p/p$ greater than $1.5{\times}10^{-3}$ and the LIU specifications were fulfilled, in addition no particle losses were observed.

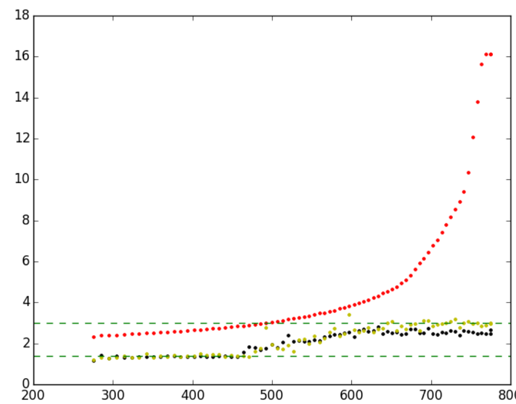

Figure 11: Emittance evolution with constant 16 kV starting from a 1.4 eVs bunch and injecting noise during the interval [C450-C600]. The foot tangent (yellow) and vertical cut (black) conventions are used to determine the corresponding emittances; the bucket area is in red.

CONCLUSION

Collective effects, as well as double RF operation in bunch-lengthening mode, phase loop and emittance blow-up are currently of fundamental importance in PSB operation, which will be the same in the post LS2 scenario. We showed that the BLonD code takes into account all these features and we gave examples of realistic simulations for the nominal LHC beam. We were able to blow up the emittance, as requested by LIU project, injecting phase noise in single RF. Further studies and simulations with intensity effects combining together blow-up, phase loop and double RF will complete the picture.

ACKNOWLEDGEMENT

We should thank the BLonD team at CERN. A special thank goes to A. Lasheen and J. E. Muller for valuable discussions on how to correctly implement intensity effects in low energy machines. Finally all the following people at CERN gave important help or support: M. E Angoletta, E. Benedetto, A. Blas, V. Forte, K. Hanke, M. Paoluzzi and G. Rumolo.

ISBN 978-3-95450-178-6

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ISBN 978-3-95450-178-6