SIMULATED PERFORMANCE OF AN FIR-BASED FEEDBACK SYSTEM TO CONTROL THE ELECTRON CLOUD SINGLE-BUNCH TRANSVERSE INSTABILITIES IN THE CERN SPS*

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Abstract

The operation at high current of high-energy proton machines like the SPS at CERN is affected by transverse single-bunch instabilities due to the Electron Cloud effect [1]. As a first step towards modeling a realistic feedback control system to stabilize the bunch dynamics, we investigate the use of a Finite Impulse Response (FIR) filter to represent the processing channel. The effect of the processing channel on the bunch dynamics is analyzed using the macro-particle simulation package Warp-Posinst. We discuss the basic features of the feedback model, report on simulation results, and present our plans for further development of the numerical model.

INTRODUCTION

Electron clouds in the SPS at CERN are responsible for the occurrence of large and fast growing transverse instabilities in high-intensity proton beams. A feedback (FB) control system to damp transverse instabilities has been proposed and is currently under study [2]. The particle-in-cell, macroparticle simulation code suite Warp-Posinst is being used to model the dynamics of the beam-electron interaction and the action of the feedback system on the beam with the intent to determine the basic requirements for the FB system such as minimum bandwidth and amplitude of the kicker signal necessary to achieve stability.

Figure 1 shows a schematic of the control loop.

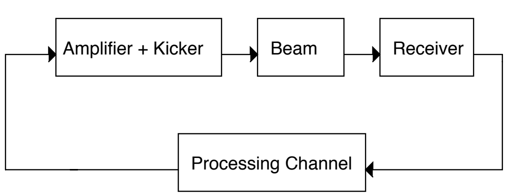

Figure 1: General scheme of the SPS Ecloud Feedback Control System.

The processing channel discussed in this paper is based on a simple bandpass FIR filter, which is more realistic than the model utilized in previous studies [3]. The filter limits the bandwidth around the nominal betatron tune frequency, eliminating spurious signals and advancing the phase at the tune frequency. Single-bunch simulation results are presented comparing open (FB off) and closed (FB on) loop cases and analyzing the vertical motion of bunch slices. The model of the kicker is ideal and has no bandwidth limitation. As a first pass towards evaluating the gain requirement of the amplifier driving the kicker, we performed several simulations limiting the kick signal to a nominal saturation level and studied how this affects the control of the beam dynamics. Conclusions and future developments of the numerical model are discussed in the last section.

FEEDBACK MODEL

The simple $5-$tap band-pass FIR filter used in our studies damps the beam vertical motion while limiting the bandwidth around the nominal fractional tune $[Q_y] = 0.185$ and performing a phase advance of 90 deg around the nominal tune value. The filter has 5 taps, *i.e.* it is based on 5 previous measurements $y_i(k)$ of the bunch vertical displacement taken at a fixed location around the ring. The output $z_i(k)$ is calculated as

$$z_i(k) = a_1 y_i(k-1) + a_2 y_i(k-2) + ... + a_n y_i(k-n) \quad (1)$$

where $i = 1, \cdots, N_{\text{slices}}$ identifies the bunch slice, k is the machine turn no., $n = 5 =$ is the # of taps, and the set of coefficients $a_1, a_2 ... a_n$ define the impulse response of the filter. This set of coefficients depends on the design of the transfer function chosen. The FIR Bode plot is reported in Fig. 2.

The output signal of the filter is used to kick each slice of the bunch. The kick is applied on a one-turn delay basis at the position along the accelerator where the beam is sampled.

The action of the feed-back system can be represented in terms of the following simplified linearized model of bunch dynamics

$$y'' + \omega^2 y = K(y_e - y) + \Delta_{p_\perp}, \quad (2)$$

where y is the amplitude of the transverse oscillation of a beam slice and y_e the transverse offset of the electron cloud baricenter corresponding to that slice; the constant K is a measure of the interaction between the beam and the electron cloud and $\Delta_{p_\perp}$ the signal from the kicker. A functioning feed-back will force the vertical displacement

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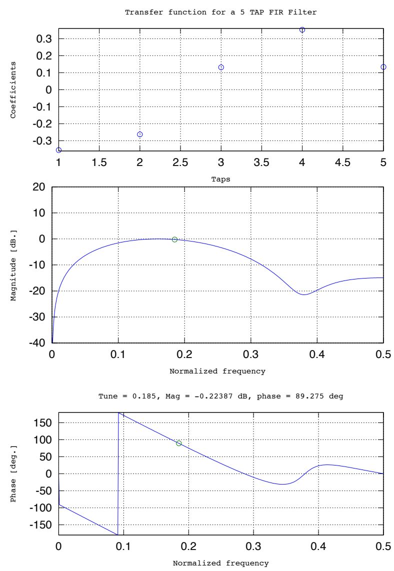

Figure 2: FIR filter Bode Plot. The frequency response has maximum magnitude 0 dB and phase 90 deg around $[Q_y] = 0.185$

of each slice of the bunch toward zero $y \simeq 0$, reducing (2) to

$$Ky_e \simeq \Delta_{p_\perp}, \tag{3}$$

suggesting that analyzing $\Delta_{p_\perp}$ will give a measure of the interaction between the e-cloud and the bunch.

SIMULATION RESULTS

Single-bunch simulations were performed at the SPS injection energy $E = 26$ GeV, assuming a uniform distribution of electrons $n_e = 10^{12} m^{-3}$ in all stations around the ring. In all cases discussed here we applied an initial uniform vertical offset to the bunch with 10% amplitude relative to σ_y. The feedback loop is closed in order to damp the beam using the FIR filter. The kicker is ideal and has no bandwidth limitation. The beam dynamics in the ring assumes a smooth approximation for the lattice. For more details on the physics model implemented in Warp-Posinst we refer to [3].

Table 1 reports the beam parameters used in all runs.

Figure 3 shows the vertical displacement of one slice in the tail of the bunch both in the open and closed loop cases. In open loop the bunch develops a strong instability due to the electron cloud, while in closed loop the oscillation is controlled and the beam transverse oscillations are well damped.

Figure 4 reports the momentum change imparted by the kicker to each bunch slice at each machine turn. Notice that in spite of the apparent stabilization of beam centroid motion (see red curve in Fig. 3) a finite signal of the kicker is still required, particularly in the head and tail of the bunch, with the tail needing a stronger kick compared to the head. We plan to carry out further studies to determine the physical basis of this behavior or a possible dependence on spurious numerical effects in the simulations.

Table 1: WARP Parameters used in the SPS simulations

Parameter	Symbol	Value
beam energy	E_b	26 GeV
bunch population	N_b	1.1 x 10^{11}
rms bunch length	σ_z	0.23 m
rms transversal emittance	$\epsilon_{x,y}$	2.8, 2.8 mm.mrad
rms momentum spread	σ_{rms}	2 x 10^{-3}
beta functions	$\beta_{x,y}$	33.85, 71.87 m
betatron tunes	$Q_{x,y}$	26.13, 26.185
chromaticities	$Q'_{x,y}$	0, 0
cavity Voltage	V	2 MV
mom. compact. factor	α	1.92 x 10^{-3}
circumference	C	6.911 km
# of beam slices	N_{slices}	64
# of stations/turn	N_s	20

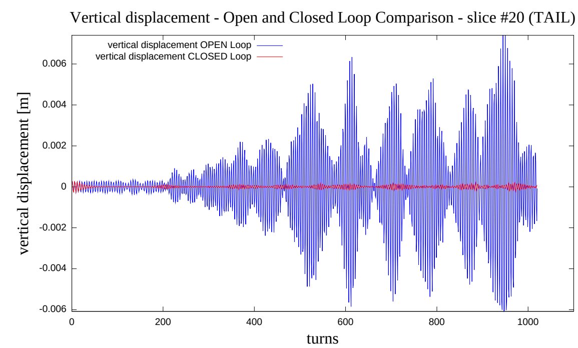

Figure 3: Comparison between open and closed loop cases of a slice vertical displacement in the tail of the bunch.

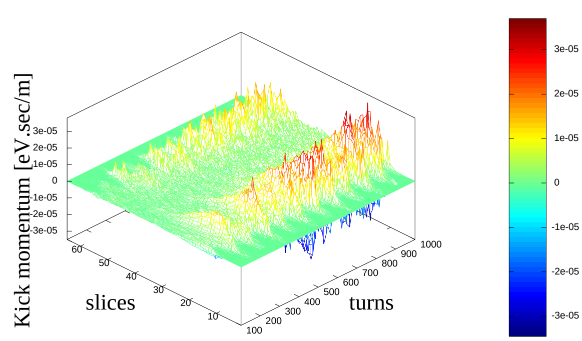

Figure 4: Momentum slices vs. turns, applied to the bunch by the kicker. The first 100 turns are cut off to avoid displaying the initial offset. Slices close to 0 represent the tail of the bunch, while slices close to 64 represent the head.

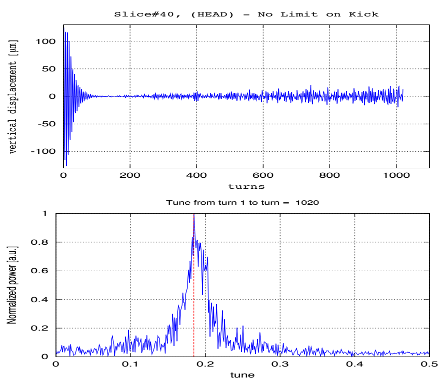

Figure 5: Vertical displacement vs. turns and fractional tune of a slice in the head of the bunch. The fractional tune has a maximum peak at $[Q_y] = 0.185$.

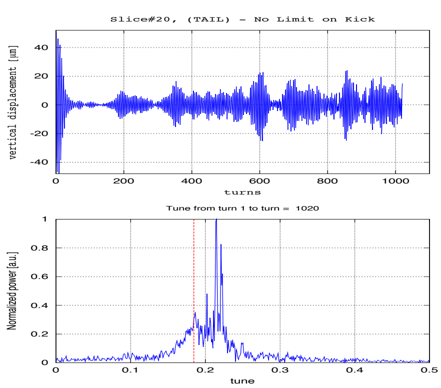

Figure 6: Vertical displacement vs. turns and fractional tune of a slice in the tail of the bunch. The fractional tune is shifted and has a maximum peak at $[Q_y] = 0.2149$.

Figures 5 and 6 show the vertical displacement and fractional betatron tune of a slice, respectively in the head and tail of the proton bunch. After the initial offset oscillation the instability is well damped in both cases. The fractional tune of the tail is characterized by a large shift, similar to the one in open-loop case, Figure 7. For the moderate value of the electron density considered in this study the filter appears to perform well in damping the instability, however we have yet to try to optimize its design.

An important issue of the system is given by the limits in terms of power of the amplifier that drives the kicker. If the amplifier saturates the value of the kicker signal could not be sufficient to control the instability. We ran simulations with the purpose of understanding the limits of the kicker efficiency in controlling the instability by forcing the kicker signal to saturate at a pre-set value.

Figure 8 shows the momentum applied to the bunch in the case of a saturation value of $2.874 \cdot 10^{-5}$ eV.sec/m in momentum units. With this constraint the beam looks initially stable but a vertical instability soon appears and

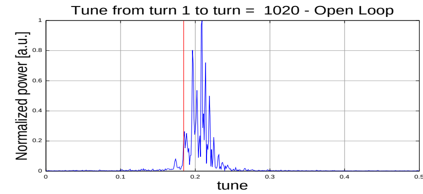

Figure 7: Fractional betatron tune of a slice in the tail of the bunch in Open Loop case. The tune is shifted and has a maximum peak at $[Q_y] = 0.20903$.

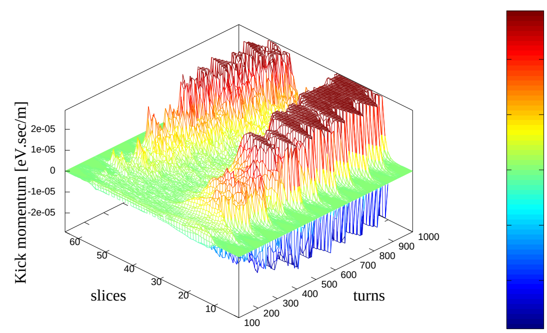

Figure 8: Momentum, slices vs. turns, applied to the bunch by the kicker, the signal is set to saturate at $2.874 \cdot 10^{-5}$ eV.sec/m. Slices close to 0 are in the tail of the bunch, while slices close to 64 are in the head.

grows exponentially as the simulation progresses. As already noticed in reference to Figure 4, even if the proton bunch is initially stabilized by the feedback the kicker needs to keep applying a momentum kick to the bunch to maintain stability. However, in this case the kicker cannot provide all the required correction signal due to the imposed limitation on the maximum voltage allowed. Finally, notice that the instability appears larger in the bunch tail, Figure 9, compared to the bunch head, Figure 10, and in both cases the beam tune is shifted.

CONCLUSION

Transverse single-bunch instabilities have been observed in the SPS at CERN due to e-cloud effects and are acknowledged as possible serious limitation to any future intensity upgrade of the LHC injection complex. A feedback control system could help overcome these limitations and represents an attractive potential solution. As part of the R&D required for a feasibility study we have started to carry out numerical simulations using the Warp-Posinst code to model the effect of a feed-back system on the beam in the presence of e-cloud. See also [5]. A simple FIR filter has been used as an improvement on previous approaches to represent the processing channel in the feedback loop model.

Single-bunch simulations using an ideal kicker show that the feedback system is effective at suppressing the vertical instability that would otherwise appear in the presence of

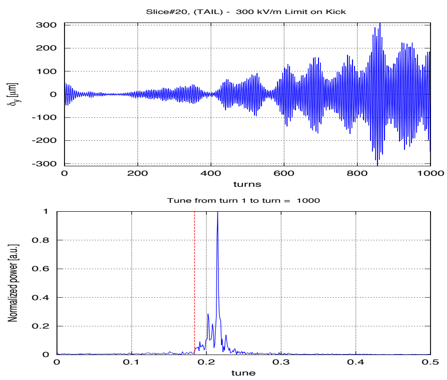

Figure 9: Vertical displacement vs. turns and fractional tune of a slice in the Tail of the bunch. The kicker signal saturates at $2.874 \cdot 10^{-5}$ eV.sec/m. The instability grows larger and faster compared to the head. The tune is shifted to $[Q_y] = 0.2152$.

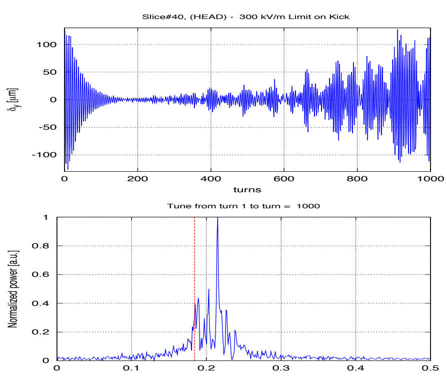

Figure 10: Vertical displacement vs. turns and fractional tune of a slice in the head of the bunch. The kicker signal saturates at $2.874 \cdot 10^{-5}$ eV.sec/m. The beam becomes increasingly unstable and the fractional tune maximum peak is shifted to $[Q_y] = 0.2152$.

a $n_e = 10^{12} m^{-3}$ e-cloud density. The vertical motion of the bunch is well damped when no limitation is imposed to the amplitude of the kick signal but a vertical instability eventually reappears in the case where a saturation level of $2.874 \cdot 10^{-5}$ eV.sec/m in momentum is imposed on the kicker field.

Future improvements of the numerical model will include the frequency response of the receiver and the kicker, downsampling the beam from $N_{slices} = 64$ to a more realistic $N_{slices} = 8$, and adding noise in the loop to investigate the minimum gain required for stability.

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