Title

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SIMULATION RESULTS OF A FEEDBACK CONTROL SYSTEM TO DAMP ELECTRON CLOUD SINGLE-BUNCH TRANSVERSE INSTABILITIES IN THE CERN SPS[*]

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Abstract

Transverse Single-Bunch Instabilities due to Electron Cloud effect are limiting the operation at high current of the SPS at CERN. Recently a high-bandwidth Feedback System has been proposed as a possible solution to stabilize the beam and is currently under study. We analyze the dynamics of the bunch actively damped with a simple model of the Feedback in the macro-particle code WARP, in order to investigate the limitations of the System such as the minimum amount of power required to maintain stability. We discuss the feedback model, report on simulation results and present our plans for further development of the numerical model.

INTRODUCTION

The Electron Cloud Instability (ECI) represents a limitation to future intensity upgrades of the LHC injection complex at CERN, [1], [2]. Large and fast growing transverse instabilities have been reported affecting high-intensity proton beams in the SPS. One of the solutions proposed to mitigate this effect is a high-bandwidth Feedback (FB) Control System, [3]. We used the extensive capabilities of the PIC simulation framework WARP to model the bunch interaction with the e-cloud together with the damping action provided by a simple and ideal Feedback. Our purpose is to investigate the requirements of the System such as the minimum amount of power required to maintain stability. The control action is based on a bandpass FIR filter (refer to [4] for more details on filter design). We ran several simulations using a fixed set of initial parameters, evaluating the beam instability growth rate and adjusting the filter gain accordingly to achieve stability, comparing open (FB off) and closed (FB on) loop cases and analyzing vertical instabilities and emittance growth. After setting a constant filter gain value simulations have been performed limiting the kick signal with different saturation levels and varying the electron density around the accelerator ring, as a first step to evaluate the minimum amount of power needed to control efficiently the transverse motion in relation to the e-cloud density. Conclusions and future developments of the numerical model are discussed in the last section.

FEEDBACK MODEL

The Feedback is composed by three elements connected in a loop: a receiver measures and processes the signal from the pick-up and estimates the vertical displacement of different areas on the bunch, a processing channel calculates the control signal and finally the signal is amplified and applied to the bunch by a kicker, [5]. The output signal of the FB is applied to each slice of the bunch on a one-turn delay basis at the same position along the accelerator where the beam is sampled. The processing channel is represented by a simple FIR filter that damps the beam vertical displacement while limiting the bandwidth around the nominal fractional tune $[Q_y] = 0.185$ and advancing the phase by 90 degrees at the tune frequency. The output $z_i(k)$ of the FIR is calculated on 5 previous measurements of the bunch vertical displacement $y_i(k)$ 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 number, $n = 5$ is the # of taps and the set of coefficients $a_1, a_2 ... a_n$ defines the impulse response of the filter. The complete FIR output with gain G can be defined as $C_i(k) = G \cdot z_i(k)$. The receiver and kicker are ideal and have no bandwidth limitation. The action of the Feedback system can be understood 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 vertical oscillation of a 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 beam-ecloud and $\Delta_{p_\perp}$ the signal of the kicker. With the Feedback on, the vertical displacement of each slice is forced to zero, $y \simeq 0$, reducing (2) to

$$|K y_e| \simeq |\Delta_{p_\perp}|, \quad (3)$$

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

SIMULATION RESULTS

The set of initial parameters used in all simulations is reported in Table 1.

Several Single-Bunch simulations were performed setting an initial vertical offset $\delta_y = 0.1 \cdot \sigma_y = 0.269$ mm to all the bunch slices and assuming a uniform distribution of electrons $n_e = 10^{12} m^{-3}$ at each station around the ring.

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Table 1: WARP Parameters Used in the SPS Simulations

Parameter	**Symbol**	**Value**
beam energy	E_b	26 GeV
bunch population	N_b	1.1×10^{11}
rms bunch length	σ_z	0.229 m
rms transv. emittance	$\epsilon_{x,y}$	2.8, 2.8 mm·mrad
rms longit. emittance	ϵ_z	0.0397 eV·s
rms momentum spread	δ_{rms}	1.9×10^{-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
RF cavity Voltage	V	2 MV
mom. compact. factor	α	1.92×10^{-3}
circumference	C	6.911 km
# of beam slices	N_{slices}	64
# of stations/turn	N_s	20

The beam in open loop starts undergoing a growing vertical instability for $n_e = 0.5 \cdot 10^{12} m^{-3}$. A preliminary estimation of the bunch interacting with the e-cloud in open loop gave a vertical instability growth rate between 1/20 - 1/50 turns. With gain $G = 0.1$ the FIR filter is able to damp growth rates slower than 1/20 turns, consequently a value of $G > 0.1$ is needed to efficiently damp the transverse motion of the slices. Fig. 1 shows the absolute value of the vertical motion of the bunch centroid in open loop (FB off) compared with the closed loop case (FB on). When the Feedback is active with $G = 0.1$ the damping action of the filter allows a strong reduction of the vertical instability and emittance growth, Fig. 2, albeit insufficient as the emittance increases by about 40% after 2000 turns. Using a gain $G = 0.2$ provides an even greater control with no detected emittance growth after 2000 turns.

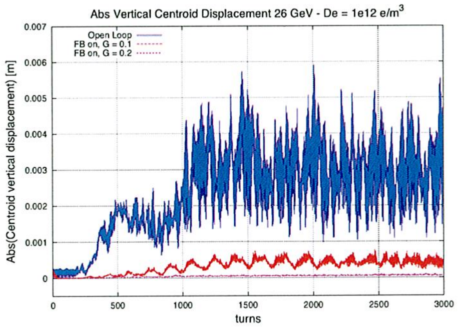

Figure 1: Absolute value of the bunch centroid vertical displacement vs turns. The centroid is calculated averaging the vertical displacement of the bunch over 64 slices.

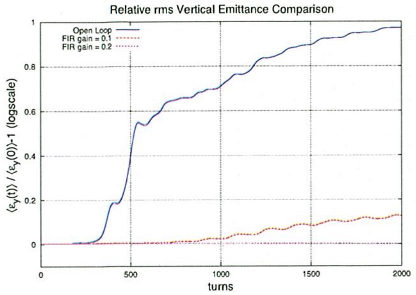

Figure 2: Relative vertical rms emittance growths in open loop (blue) and closed loop setting $G = 0.1$ (red) and $G = 0.2$ (magenta).

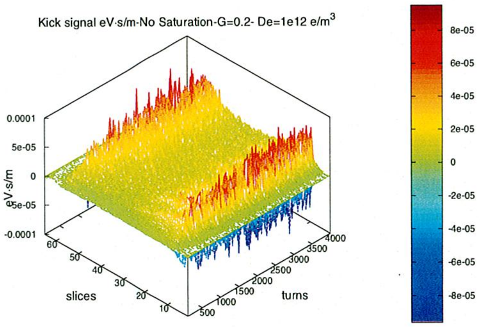

Figure 3: Kick signal eV·sec/m, slices vs turns. Gain $G = 0.2$. Slices close to 1 correspond to the bunch tail.

Fig. 3 shows the momentum applied to the bunch in eV·sec/m units in the case of Fig. 1 with FB on and $G = 0.2$ (low vertical instability). The Power Spectral Density of the kick signal ($\Delta_{p_\perp}$ according to Eq. 3) in this case is reported in Fig. 4, the power over turns increases spreading over the spectrum of frequencies but most of it is concentrated in the bandwidth within 1 GHz. One of the limitations of the system is given by the amplifier that drives the kicker. If the amplifier saturates the kicker signal could not be sufficient to damp the instability efficiently. We ran simulations keeping the FIR gain $G = 0.2$ and forcing the kicker signal to saturate at an arbitrary value in momentum units with the purpose of understanding the limits of the kicker efficiency in controlling the transverse instability. In the results shown we considered two saturation levels at $9.58 \cdot 10^{-6}$ eV·sec/m and $2.874 \cdot 10^{-5}$ eV·sec/m, respectively about 10% and 30% of the maximum momentum measured in the case with no limitation (Fig. 3).

We choose two slices as representative of the behavior of the tail (blue trace) or head (red trace) areas in the bunch. In Fig. 5 is reported the kick signal limited at $9.58 \cdot 10^{-6}$ eV·sec/m (top) and the correspondent vertical displacement (bottom). All the slices are initially damped, slices in the tail area require more power to be controlled (as in Fig. 3) and the kick signal is saturated faster respect to the head. After 1200 turns a large growing instability shows up and

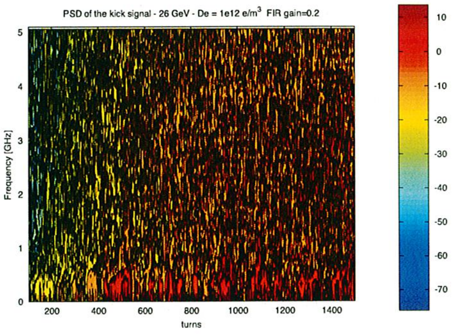

Figure 4: Power Spectral Density of the kicker signal, frequencies vs turns, dB units.

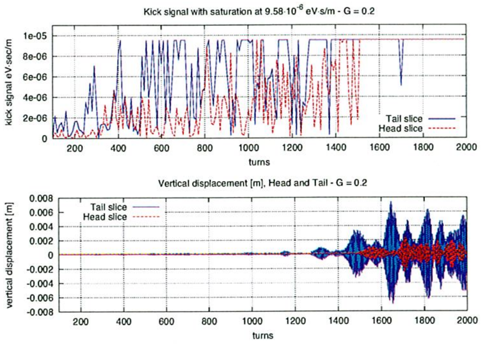

Figure 5: Absolute value of the kick signal limited at $9.58{\cdot}10^{-6}$ eV·sec/m (top) and vertical displacement (bottom) for a slice in the tail (blue) and in the head (red).

a similar effect occurs in the head a few turns later. If the kick signal is limited at $2.874{\cdot}10^{-5}$ eV·sec/m, Fig. 6, all slices are damped in this range of turns and the kick signal do not saturate. In Fig. 7 we keep a saturation threshold of $2.874{\cdot}10^{-5}$ eV·sec/m but we set a density of electrons $n_e = 2 \cdot 10^{12} m^{-3}$. In this case the maximum signal able to be processed by the amplifier and kicker is not enough to control the instability, when the power stage saturates the slices are affected by large transverse oscillations.

CONCLUSION

Large and fast growing transverse instabilities in high-intensity proton beams represent a limitation for future upgrades of the SPS operation at high current. A high-bandwidth Feedback Control System could be a potential solution to this problem. We have started to investigate System requirements and limitations using WARP simulation framework, starting from a simplified model of the Feedback based on a FIR filter. Single-Bunch simulations with gain $G = 0.2$ and e-cloud density $n_e = 10^{12} m^{-3}$ show a well damped vertical motion of the bunch. However the control action fails and a growing instability shows up in the case of a limitation on the kicker signal of $9.58{\cdot}10^{-6}$ momentum. In addition setting a larger electron density value increases the beam-ecloud interaction and more power is needed to damp the beam efficiently. We are currently improving the feedback model including more realistic models for the receiver, power amplifier and kicker. We plan to continue to study the bunch dynamics in closed and open loop for different electron densities. We still need to investigate more accurately if the effects seen in the simulation are caused by the beam physics or resulting from aspects of the numeric simulation.

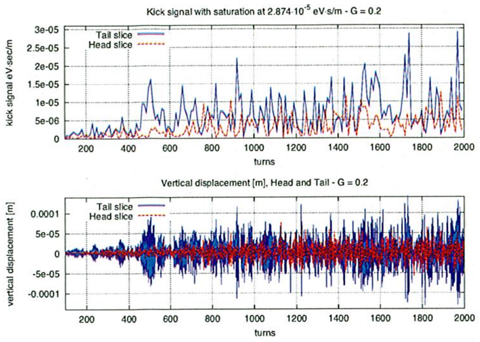

Figure 6: Absolute value of the kick signal limited at $2.874{\cdot}10^{-5}$ eV·sec/m (top) and vertical displacement (bottom) for a slice in the tail (blue) and in the head (red) of the bunch. The uniform electron density is $n_e = 1 \cdot 10^{12} m^{-3}$.

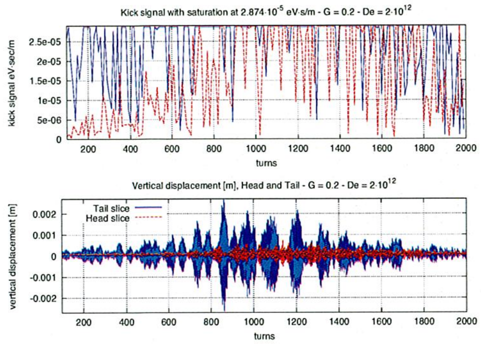

Figure 7: Absolute value of the kick signal limited at $2.874{\cdot}10^{-5}$ eV·sec/m (top) and vertical displacement (bottom) for a slice in the tail (blue) and in the head (red) of the bunch. The uniform electron density is $n_e = 2 \cdot 10^{12} m^{-3}$.

REFERENCES

[1] G. Arduini et al., CERN-2005-001, (2005) 31-47

[2] G. Rumolo et al., PRL 100 (2008) 144801

[3] J. D. Fox et al., Proc. of IPAC 2010, Kyoto, Japan.

[4] R. Secondo et al., Proc. of ECLOUD 2010, Cornell University, NY, USA.

[5] J.-L. Vay et al., Simulation of E-Cloud Driven Instability and its Attenuation Using a Feedback System in the CERN SPS, Proc. of IPAC 2010, Kyoto, Japan.

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