CONTROL OF INTRABUNCH DYNAMICS AT CERN SPS RING USING 3.2 GS/s DIGITAL FEEDBACK CHANNEL*

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Abstract

The feedback control of intra-bunch instabilities driven by electron-cloud or strong head-tail interaction requires bandwidth sufficient to sense the vertical position and apply correction fields to multiple sections of a nanosecond-scale bunch. These requirements impose challenges and limits in the design of the feedback channel.

We present experimental measurements taken from the CERN SPS machine development studies with an intra-bunch feedback channel prototype. The performance of a 3.2 GS/s digital processing system is evaluated, quantifying the effect of noise and limits of the feedback channel in the bunch stability as well as transient and steady state motion of the bunch. The controllers implemented are general purpose 16 tap FIR filters and the impact on the bunch stability of controller parameters are analyzed and quantified. These studies, based on the limited feedback prototype, are crucial to validate reduced models of the system and macro-particle simulation codes, including the feedback channel. These models will allow us to predict the beam dynamics and controller limits when future wideband hardware is installed in the final prototype to stabilize multiple bunches.

INTRODUCTION

Intrabunch instabilities induced by electron-cloud (ECI) and strong head-tail interactions (TMCI) limiting factors to reach the maximum beam currents in the SPS and LHC rings [1]. Feedback techniques can stabilize bunch instabilities induced by electron cloud and strong head-tail interactions. The application of feedback control to stabilize the bunch is challenging because it requires large bandwidth to sense the transverse position and apply correcting fields to multiple sections of a nanosecond-scale bunch. These requirements impose technology challenges and limits in the design. The goal is to design a feedback control channel and to develop the hardware of a control system prototype to prove principles and evaluate the limitations of this technique by stabilizing a few bunches in the CERN SPS machine. This paper presents results from measurements conducted at SPS and validation studies of models of the feedback system using those measurements.

FEEDBACK SYSTEM

A single bunch wideband digital feedback system has been developed to explore new technology and control techniques. The implementation of this system is based on a reconfigurable FPGA and ADC/DAC operating at 3.2 GS/s. The system is synchronized with the SPS RF clock and is able to perform diagnostic functions, set feedback parameters and record the bunch motion at selected intervals [2]. The present studies were conducted using an existing stripline device as a kicker with 160 MHz bandwidth. Future tests will be conducted using new wideband kickers, which are currently under development [3]. The four-electrode kicker is driven by 4- 90W amplifiers of 1GHz bandwidth. The pickup signal is equalized to compensate the frequency response of the device and the cables. The controller is implemented using a bank of simple FIR filters, processing each individual ADC samples across the bunch. The prototype is capable of setting 16-tap filters, and during the test 5-taps and 7-taps were used. Additionally, the filter parameters can be changed during the run, allowing to vary the controllers in the feedback system to process the bunch motion signals.

Feedback Model

The block diagram of the feedback system including noise sources and external signal perturbations is depicted in Fig. 1. The main blocks in this figure are modeled in both macro-particle simulation codes and tools where the bunch dynamics is represented by reduced order models to assess the stability margins of the system and study the bunch performance under the influence of noise and external perturbations. These models have to be validated

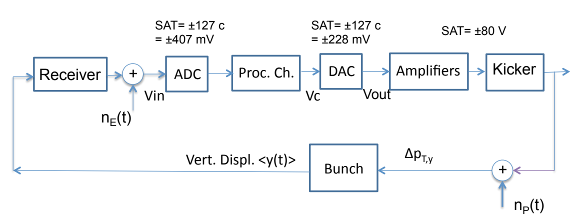

Figure 1: Block diagram feedback system.

with measurements in the SPS to be able to predict future operation conditions and evaluate the impact of limitations and non-linearities in the feedback hardware on the bunch stability and performance. The frequency response of the receiver and the RF power stage have been measured and appropriated models are included in the simulation tools [4].

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ANALYSIS OF MD DATA

In January 2013, several machine developments (MDs) where conducted to test the 3.2 GS/s digital processing prototype. The feedback system was evaluated driving and stabilizing the transverse motion of a single bunch in the SPS ring. Multiple tests were performed changing main parameters of the beam and the controller. The main goal was to evaluate the performance of the new hardware - firmware and collect data to validate simulation models and explore the limits of the feedback technique in the stabilization of the intrabunch dynamics. It will allow to predict future tests and define new hardware-firmware for operation with multiple bunches.

To quantify the overall feedback loop gain tests were conducted using the feedback system to stabilize an unstable bunch. To generate the unstable bunch, the chromaticity was changed from positive to negative after injection. The beam becomes unstable in the vertical plane, mainly with mode 0 motion. The bunch with slight positive chromaticity is injected in the machine with the feedback system in open loop and 3500 turns after injection the chromaticity is set negative decreasing slightly as a function of the turn number. If the feedback system remains in open loop, the bunch becomes unstable. Figure 2 depicts the spectrogram of the vertical motion of the centroid showing the unstable motion and the shift in the fractional vertical tune due to lost of charge. Figure 3 shows the motion of a similar bunch when it is stabilized by the feedback system. In this case, the feedback loop is closed 2000 turns after injection and the beam is stabilized. This test was repeated for different loop gains, exhibiting stable motion for gains above a certain minimum value. Using the results of these tests

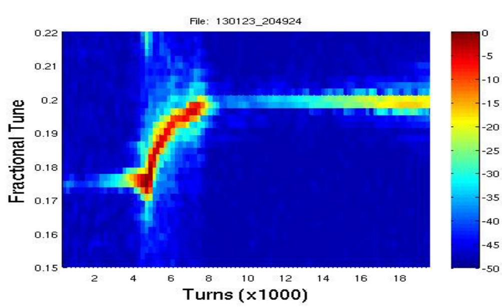

Figure 2: Spectrogram unstable bunch.

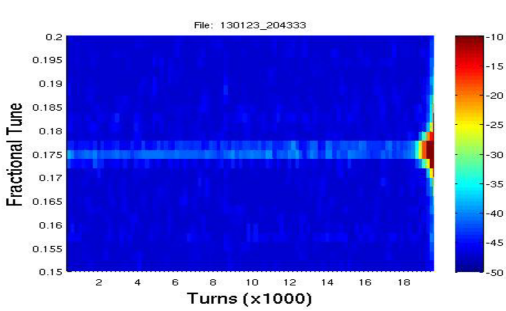

Figure 3: Spectrogram stable bunch.

with unstable beam and the feedback system operating in either open loop or closed loop, it is possible to characterize the overall loop gain of the system. It allows setting the gain of the different blocks in Fig. 1 combining additional information related to the transfer function of the feedback stages. To quantify the loop gain, the growth rate of the unstable motion of the bunch centroid was measured with the feedback system in open loop or in closed loop with low gain. The time interval to measure the growth rate was limited to make sure the measurement is conducted preserving the bunch charge. A summary of these measurements and the results of the growth rate estimation based on a simplified model of the feedback loop are shown in Fig. 4. Given the direct proportionally between the chromaticity and the number of turns, the growth time constant is plotted vs. the turn numbers or the chromaticity. The blue points depict the growth time constant measured when the feedback is in open loop and in closed loop with gains equal to 2 and 4 (unstable cases). The estimated time constants based on a simplified model for the damping are shown by the red circles. The green curve is a fitting to the growth time constant of the bunch vs. chromaticity if the feedback loop is open. The growth time constant (inverse of growth rate) decreases as a function of the number of turns because the chromaticity decreases slightly after switching from positive to negative. Assuming the simplified model for the damping bunch damping $\sigma_f(\xi) = 1/\tau_f(\xi) = 1/\tau_{OL}(\xi) - \sigma_D$, with ξ chromaticity, $\sigma_D = \sigma_1 G$ and G the controller gain, the constant is $\sigma_1 = 5.47 \times 10^{-4}$ turns^{-1}. This estimation defines the critical gain to stabilize the vertical mode 0 motion of the bunch. For example, to stabilize an unstable bunch with a growth rate $\sigma_{OL} = 0.01$ turns^{-1} ($\tau_{OL} = 100$) turns a gain $G > 17$ is necessary. More precise analysis of this

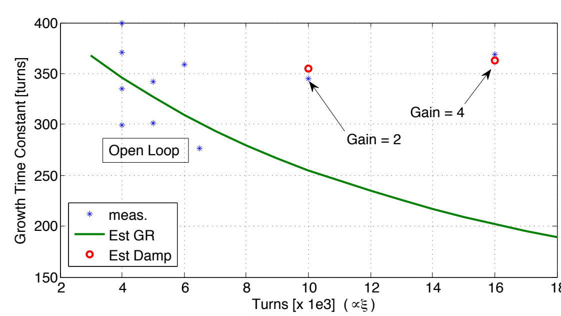

Figure 4: Growth time constant vs. chromaticity for open loop and closed loop G =2, 4.

motion was conducted via simulation using macro-particle simulation codes and a reduced models of the bunch dynamics. Using a reduced model of the bunch and representative model of the feedback system, the results depicted in Fig. 4 can be reproduced. For that case, motion of the bunch centroid was studied, with a 5-tap FIR filter and appropriated gains for the receiver and RF power stage. Figure 5 shows the results for the feedback system in open loop when the parameters of the bunch are set to define a growth time constant equal to $\tau_{OL} = 200$ turns. Figure 6 shows the unstable motion of the bunch centroid with the

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feedback gain $G = 4$, giving a $\tau_f = 360$ turns. Similar agreement of the final growth rate with the results depicted in Fig. 4 were obtained when the gain was set to $G = 2$.

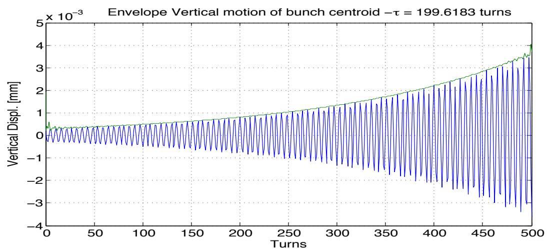

Figure 5: Unstable motion of the beam corresponding to $\tau_{OL} = 200$ turns in Fig. 4 - Open loop feedback - Reduced model simulation

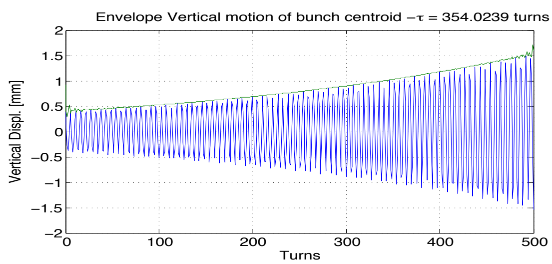

Figure 6: Unstable motion of the beam with feedback in closed loop and gain $G = 4$. - $\tau_f = 360$ turns in Fig. 4 - Reduced model simulation

Using macro-particle simulation codes and appropriated models for the receiver and RF power stages, the damping behavior can be reproduced as well.

Several parameters in the controller have been changed and the response of the bunch motion has been measured to quantify the robustness of the feedback system. Furthermore, this data displays how well the models are able to predict the effect of those variations in the stability and performance of the feedback system. The controller is parameterized by two variables, the gain G and the phase ϕ. Additionally, another important parameter in the feedback loop is the timing between the bunch position and both the ADC samples and the kicker signal. Other important parameters for the design of the overall system are the kicker-amplifier bandwidth and amplifier maximum power, and their impact in the feedback stability and performance are evaluated using simulations and reduced models for the system. In this paper, we show results of the impact on the stability of changes in the controller parameters G and ϕ. The nominal controller is set with a phase $\phi = 70^o$ giving a almost pure damping without changing the betatron tune. When the phase of the controller is set to $\phi = 30^o$ the tune frequency is changed for increasing gain. Figure 7 shows the fractional tune for different samples across the bunch when the feedback is in open loop around turns 0-2000, while Fig. 8 depicts the closed loop case with $G = 64$ and $\phi = 30^o$ for turns 4000-6000. It can be observed the tune shift from $f_\beta = 0.177$ to $f_\beta = 0.183$. Similarly, if the gain is set to $G = 16$ with $\phi = 30^o$ the fractional tune changes from $f_\beta = 0.177$ to $f_\beta = 0.178$. Figure 9 summarizes these measurements and compares them to the values of the complex dominant eigenvalues for the feedback system calculated from a simplified model of the bunch.

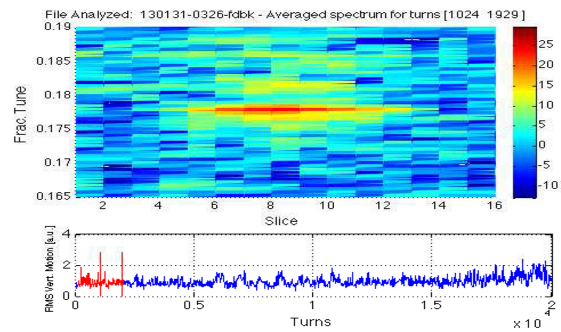

Figure 7: Fractional tune for multiple longitudinal samples of the bunches for feedback system in open loop.

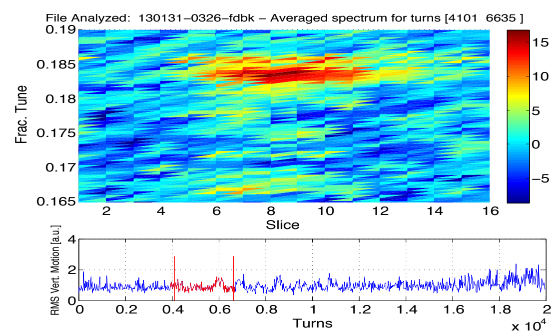

Figure 8: Fractional tune for multiple longitudinal samples of the bunches for feedback system in closed loop with $G = 64$ and $\phi = 30^o$.

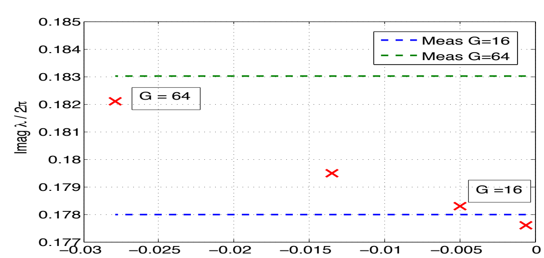

Figure 9: Location of dominant eigenvalues of the feedback system for $\phi = 30^o$ and increasing gain estimated from analytical model. Comparison with the measured fractional tune.

CONCLUSIONS

Several MDs were conducted at CERN SPS before the long shutdown. It allowed to commission and evaluate the performance of a 3.2 GS/s feedback channel prototype and collect data to validate macro-particle simulation codes and reduced models. We presented some results from these studies and the matching with the estimated parameters given by the simulation tools. Further analysis is in progress to analyze the bunch dynamics and quantify the models based on data collected when the bunch was driven by different excitations.

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