BROAD-BAND TRANSVERSE FEEDBACK AGAINST E-CLOUD OR TMCI: PLAN AND STATUS*

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Abstract

The feedback control of intra-bunch instabilities driven by electron-clouds or strong head-tail coupling (Transverse mode coupled instabilities, TMCI) requires bandwidth sufficient to sense the vertical position and apply multiple corrections within a nanosecond-scale bunch. These requirements impose challenges and limits in the design and implementation of the feedback system. To develop the feedback control prototype, different research areas have been pursued to model and identify the bunch dynamics, design the feedback control and implement the GigaHertz bandwidth hardware. This paper presents those Research & Development lines and reports on the progress as it stands today. It presents preliminary results of feedback systems stabilizing the transverse intra-bunch motion, based on macro-particle simulation codes (CMAD / HeadTail) and measurement results of the beam motion when it is driven by particular excitation signals.

INTRODUCTION

Intrabunch instabilities induced by electron clouds and strong head-tail interactions are one of the limiting factors to reach the maximum beam currents in the SPS and LHC rings[1, 2]. Different schemes to control both electron cloud instabilities (ECI) and transverse mode coupling instabilities (TMCI) are under investigation to achieve the required High Luminosity in LHC. The effect of coating the SPS vacuum pipes with low secondary electron yield materials has been studied to effectively suppress the electron cloud build-up, and mitigate intrabunch ECI. CERN is proposing a plan to coat large part of the SPS and LHC chambers in order to mitigate electron cloud instabilities. Continuous testing of the limitations of these techniques and the design of the necessary infrastructure to apply the coating are currently conducted at CERN [3]. These techniques cannot mitigate TMCI and research is conducted at CERN to lower the transition energy in the SPS and thus increasing the synchrotron tune which has shown to increase the instability threshold for TMCI[2, 4].

Feedback techniques can stabilize bunch instabilities induced not only by electron clouds but also induced by strong head-tail interactions (TMCI). Complementary to the plan previously described, the US LHC Accelerator Research Program (LARP) is supporting a collaboration between US Labs and CERN to study the viability of controlling intrabunch instabilities using feedback control techniques. A collaboration among SLAC / LBNL / CERN (under the DOE LARP program) started evaluating the limitations of this technique to mitigate both instabilities and other possible head-tail distortions in bunches [5, 6].

The application of feedback control to stabilize the bunch is challenging because it requires a bandwidth sufficient 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 [7]. Additionally, the intra-bunch dynamics is more challenging than the beam dynamics involving the interaction between bunches. The collaboration has defined different interdependent working lines to study the problem, 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 gives an overview of the research areas and plans, measurements and results of present studies, and goals and future directions.

RESEARCH & DEVELOPMENT - GOALS

A CERN - US collaboration has been working to mitigate via GigaHertz bandwidth feedback systems electron clouds, TMCI, and other intra-bunch distortions and instabilities at SPS and LHC. The near term goal for this ECI/TMCI feedback is to analyze and define design techniques for the system, study the limitations of the feedback technique to mitigate those instabilities, and build the hardware of a minimum prototype to control a few bunches and measure the limiting performance. the design of a practical prototype system capable of controlling a full SPS fill is a future project based on the results of this first stage.

The collaboration has defined different working lines that involve:

1. Development of reduced mathematical models of the bunch dynamics interacting with electron clouds and machine impedances. Identification of those reduced models based on machine measurements. Design of control feedback algorithms based on the reduced models.

2. Inclusion of realistic feedback models in advanced multi-particle simulation codes to test the models, possible feedback designs and diagnostic tools.

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3. Measurements in the SPS machine to validate both the reduced and multi-particle models.

4. Development of hardware prototype of feedback control processing channel.

5. Development of hardware prototypes of wide band pick-ups and kickers to sense and drive vertically bunch.

The main goal is to model the bunch dynamics using both reduced mathematical models and multi-particle non-linear models and validate them via real measurements in the machine. It allows to perform model-based design of the feedback control system including uncertainties, signal perturbations and noise in the channel. Multi-particle codes will define a test-bench for both the designed control algorithms and also the diagnostic tools used during the machine measurements. Based on validated and realistic models of the system, the design can be translated directly to the hardware prototype. The final performance of the system will be tested by controlling a few bunches in the CERN SPS machine. A simplified chart of this Research and Development (R & D) plan is depicted in Fig. 1. After validating and testing the feedback control prototype and evaluating cost and performance a final design, production and commissioning of the system will be conducted.

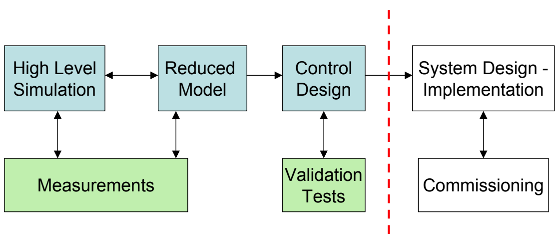

Figure 1: Simplified R & D chart for the development of the broad-band feedback control system.

HARDWARE DESIGN

General Considerations

The feedback system has to control intrabunch instabilities, requiring enough bandwidth to sense the vertical displacement of different sections of the bunch and apply multiple corrections within a nanosecond-scale bunch. These requirements impose challenges and limits in the design and implementation of the feedback system. The bunch dynamics interacting with the machine impedance (TMCI) and electron clouds is non linear and unstable above some beam current threshold. The design of a stabilizing feedback control will have multiple constraints due to the complex bunch dynamics. The original instability of the bunch will set a minimum open loop gain in the feedback system, while the intrinsic delay in the control action will limit the maximum gain. Bunch dynamic characteristics as the growth rate or tunes change intrinsically and also the beam dynamics change with the machine operation. These parameter or dynamic variations force to design robust or adaptive controllers in order to preserve the stability and performance of the feedback system in presence of those variations during operation. Additionally, the feedback control channel has to reject noise and signal perturbations affecting the system.

Feedback Control Channel

The hardware under development consists of a digital processing channel, sampling the signals at 4 Giga Samples/sec. This sampling rate is 8X faster than actual commercial bunch-by-bunch feedback units. A general block diagram of the proposed hardware is depicted in Fig. 2. The amount of multiplication/accumulate (MACs) operations in the processing channel, assuming simple architectures for the control algorithm, can exceed 5-8 Giga- MACs/sec setting a limit to the complexity of the digital processing channel.

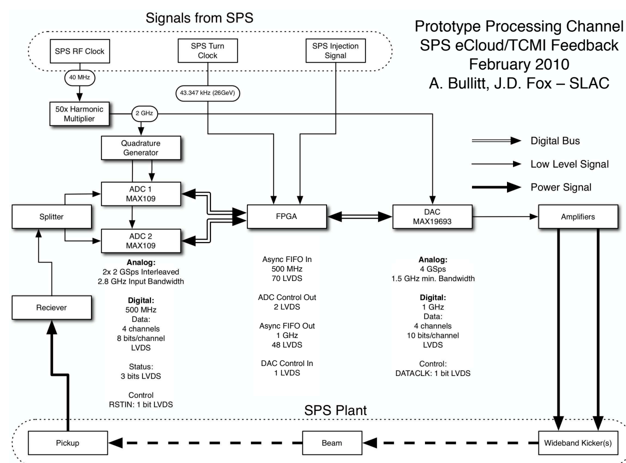

Figure 2: Block diagram of the signal flow for the initial SPS processing testbed system, intended to control a small number of bunches and explore processing algorithms.

The feedback channel is completed by wide-band pick-ups already installed in the SPS accelerator and a set of 4 amplifiers units delivering 90W with a bandwidth of 20 - 1000 MHz. The pick-ups have been originally used in the SPS ring as horizontal and vertical beam position monitors (BPM). One of the pick-ups has been used in the present set-up as a kicker to conduct studies driving the bunch. The existent pick-ups have been characterized and exhibit limitations to use them effectively as part of the feedback system. Mainly, there are resonances in the chambers holding the pick-ups strip-lines, limiting the maximum frequency of the signal detected to 1.7 GHz. Similarly, the pick-up used as kicker has a limited bandwidth of about 180 MHz. One of the goal of this research is to study the best characteristics of kickers and pick-ups for the broad band feedback channel. As result, it is expected to define the best topology for those devices, and design, construct and install prototypes for wideband devices in the SPS machine during the long shut-down starting in 2013.

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Excitation System

During 2011, a prototype including the output stage (FPGA - DAC) of the digital processing channel was built and installed together with the synchronized timing system and amplifiers in the SPS ring. This excitation box allows the generation of programmable waveforms in synchronism with any bucket in the machine. The sampling rate of the signal generated is 4 G Samples/s and arbitrary waveforms can be programmed to drive any patten across the bunch and along the turns. The purpose of this prototype was two-fold, first to build the high rate electronics required by the processing channel in the final feedback prototype and second generate a programmable synchronic excitation able to drive vertically selected bunches in the SPS machine. More details about the hardware of this prototype and features of the programmable excitations are described in [8].

Demonst ation Feedback annel

A demonstration prototype based on the feedback channel depicted in Fig. 2 is scheduled to be installed in the SPS ring during Nov. 2012. The firmware will be limited to process only a single bunch with minimum complexity in the control algorithms and diagnostics. The main purpose is to test the hardware, define a method to time properly the kicker and the receiver signals to the bunch and evaluate the behavior of the feedback channel by damping the vertical motion of the bunch. During these tests, the bunch in the machine will be driven using the excitation signal, such that the bunch will oscillate forced by the external signal. After that, the feedback loop is closed and should damp the bunch motion. This simple procedure will allow to drive different vertical modes of the dipole motion of the bunch and measure the damping response of the system defined by the feedback channel. These tests will be crucial to characterize, during the shut-down, completely the dynamics of the bunch and its interaction with the feedback channel based on those measurements and results from computer simulations. Additionally, the firmware of the processor channel will updated to include more diagnostics and robust control algorithms to take advantage of the new hardware (kicker, pick-up) to be installed in SPS during the same period. The ultimate goal for this phase is to develop a demonstration feedback channel, associated pickups, wideband amplifiers and kickers capable of driving and controlling multiple bunches. The system will be the test platform to evaluate and compare processing algorithms, and start conducting studies to estimate the necessary performance and specifications, as well as limitations, of feedback techniques in mitigating ECI and TMCI.

EXCITATION OF THE VERTICAL INTRABUNCH MOTION

Using the excitation system single bunch studies have been made in the SPS where the vertical motion in response to various excitations is recorded. Part of the motivation for this test includes developing critical timing and diagnostic techniques, as well as dynamics studies exciting various head-tail bunch resonances to quantify the intrabunch motion. Additionally, it is planned to expand these techniques into a general-purpose beam diagnostic tool to study the evolution of the bunch tunes and modal patterns of motion. We were able to excite multiple modes by driving a beam with low chromaticity. Several results of these studies have been presented in [9].

In this paper a particular example is shown. With the machine set to low chromaticity, the betatron fractional tune was $f_\beta = 0.181$ and the synchrotron tune was $f_s \simeq 0.004$. The excitation signal was applied from turn 2000 to 17000 and the frequency was swept from f/f_{REV} : $0.175 - 0.188$. Figure 3 shows the power spectrum of the vertical motion of a particular slice in the bunch. In this spectrogram, it can be observed the excitation signal that chirps through the modes 0, 1, 2, and 3. As the chirp frequency corresponds to the betatron tune and synchrotron sidebands, the resonance becomes visible. Figure 4 shows the time domain representation of the same data as Fig. 3. At turns 13401 - 13426, the equalized delta signal of the vertical motion shows multiple modes, as can be seen when comparing with the spectrogram in Fig. 3.

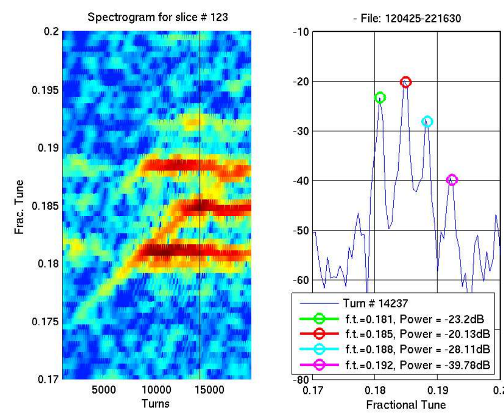

Figure 3: A spectrogram showing excitation of many intra-bunch modes for a normalized frequency (f/f_{REV})sweep from 0.175 - 0.188. The betatron frequency is $f_\beta = 0.181$ and $f_s \simeq 0.004$.

FEEDBACK CHANNEL MODEL IN MACRO-PARTICLE SIMULATION CODES

Given the actual limitations both in time and in the hardware installed in the SPS ring to test the feedback system, non-linear simulators based on macro-particle description of the bunch and e-clouds (WARP, HeadTail, CMAD) have been very useful to analyze the bunch dynamics and reduced models as well as to generate analysis tools to process the measured data [10, 11]. We have included in those simulation codes realistic models of the feedback system to have a test-bench to analyze the impact on the stability and final emittance of the bunch using a finite num-

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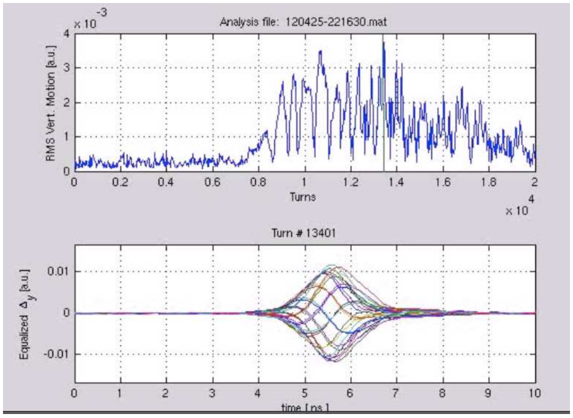

Figure 4: Top: RMS of the vertical motion. Bottom: Equalized delta signal showing multiple modes for turns 13401-13426.

ber of samples per bunch, hardware limitations, bandwidth and noise. The mathematical model of the feedback channel can be grouped in three different blocks as depicted in Fig. 5. In this plot, the feedback control system interacts with the macro-particle simulator by measuring the absolute transversal and longitudinal position of the centroid corresponding to each slice and generating a momentum or kick signal that drives each bunch slice. The control signal can be calculated based on either the absolute vertical position or the dipole moment of each slice. The feedback channel is defined by three major blocks: *the receiver* that measures and processes the signal form the beam pick-up and estimates the vertical position of the different areas of the bunch, *the processing channel* that computes, from the vertical signal, the appropriated control signal $V_C(t)$ and *the power stage* (Amplifier, Kicker) that amplifies and delivers the momentum to each slice along the bunch.

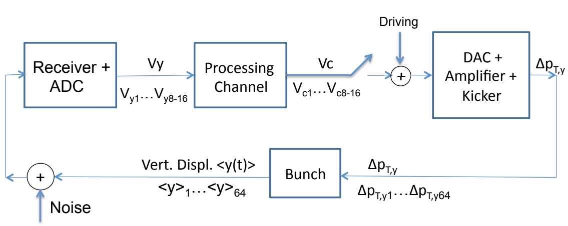

Figure 5: Block diagram of the feedback system implemented in the macro-particle code simulation.

The implementation of these blocks introduce the frequency response of the devices and limits in the level of the signals processed. Appropriated models of those blocks are necessary in the simulation of the feedback channel to understand the real limitations of the system in the stabilization of the bunch dynamics. These models define the impact of parameter variations or mismatching and the effect of spurious perturbation and noise in the performance of the feedback system. This research is crucial to evaluate the boundary in the performance of the feedback control system due to cost and technological limitations. The *receiver* and *power stage* blocks are characterized by a static map to account for non-linearities and dynamics to model the frequency response of the block. In the simulator, those blocks represent the cascade of several components in the system as the DAC, cables, amplifiers and kicker in the power block and, similarly in the receiver it accounts for the pick-up, cables, anti-aliazing filter and ADC [12].

The processing channel can include any algorithm relating samples of the input-output vectors V_Y, V_C at the same turn and multiple posterior turns, $V_C(k) = C(V_Y(k-1), V_Y(k-2), \ldots, V_Y(0))$. Signals are included additively to the feedback loop to model the noise and perturbation signals at the amplifier and the receiver due to electronic noise, pick-up noise, etc.. Additionally, the signal included in the output stage can be used to drive the bunch with different patterns.

The simulation code implemented is open enough to define different realistic models and features of the components included in the feedback channel. Additionally, sources are incorporated to represent noise and perturbation signals and evaluate their impact on the bunch performance (emittance, etc.). Models can be calculated based on actual device transfer functions or based on proposed characteristics of the device under study. Similarly, the noise and perturbation signals can be defined either based on measurements or using theoretical models.

Some results of simulations using macro-particle simulation codes (HeadTail, CMAD) are presented. Figure 6 depicts the evolution of the vertical centroid motion and the normalized y-emittance for different central cloud densities, when the feedback loop is disabled. This plot shows the impact of the ECI in the bunch motion.

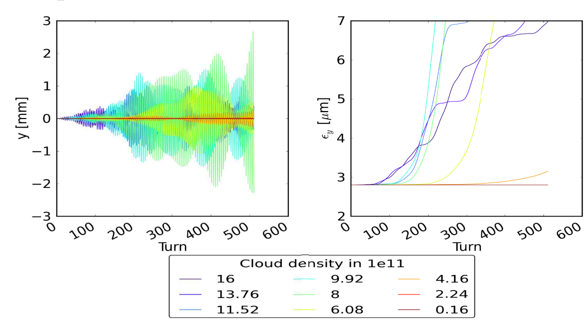

Figure 6: The evolution of the bunch centroid motion and the normalized emittance for different central cloud densities.

The impact of the kicker bandwidth in the feedback stabilization of the bunch dynamics has been analyzed modeling kickers with similar frequency response and different bandwidths. The feedback system is completed by a set of 5-taps FIR filters processing the multiples slices measured along the bunch. The bunch instability is induced by an electron clouds density of $6 \times 10^{11} e/m^3$. Figure 7 shows the evolution of the vertical centroid motion and the normalized y-emittance for different loop gains assuming the kicker bandwidth $BW = 200$MHz and $BW = 500$MHz.

Assuming a system with a kicker with a bandwidth $BW = 500$MHz, a maximum kick signal $\Delta p_{MAX} =$

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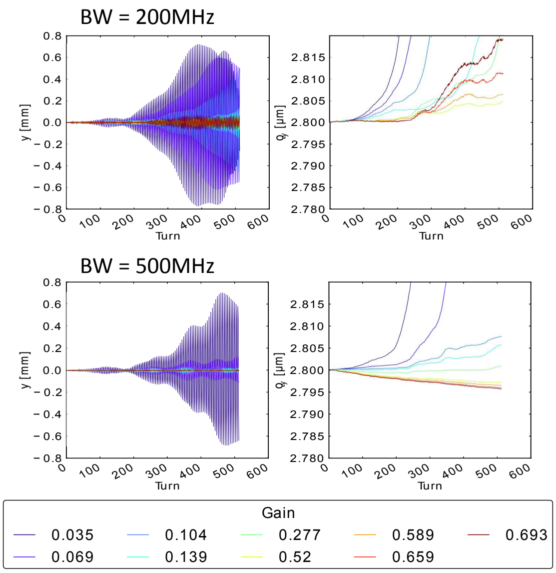

Figure 7: The evolution of the bunch centroid motion and the normalized emittance for different loop gains for kicker $BW = 200$MHz and $BW = 500$MHz.

4×10^{-5} eV s/m, the time evolution of the kicker signal and the vertical displacement of the bunch is depicted in Figs. 8 and 9 . In this particular case, the feedback system stabilizes the bunch when the electron clouds is $6 \times 10^{11} e/m^3$ and an initial transient in the vertical displacement $y_0 =$ 0.5 mm forces the saturation of the amplifier's power level, limiting the maximum kick to $\Delta p_{MAX} = 4 \times 10^{-5}$ eV s/m for several turns.

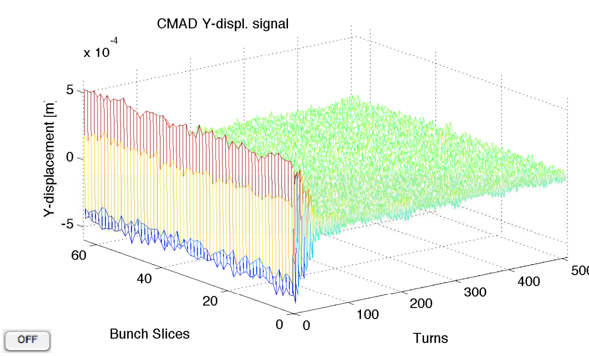

Figure 8: Vertical displacement of the multiple slices of a bunch

CONCLUSIONS

Several R/D lines have been pursued to investigate the feasibility of feedback control system to mitigate ECI and TMCI. Promising results have been achieved. A basic feedback system is going to be tested before the 2013 shutdown in SPS and ultimate tests using the final prototype will start in 2014, to validate design criteria, and evaluate performance and limitations of the feedback control technique.

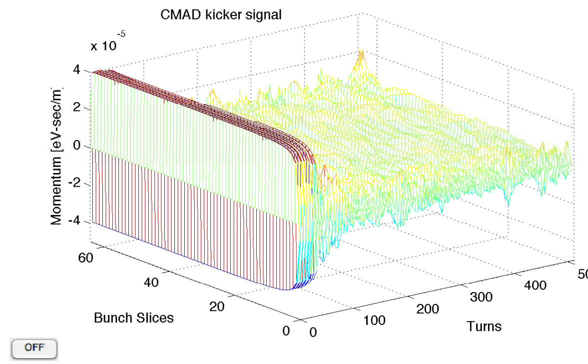

Figure 9: Momentum signal applied to multiple slices of a bunch.

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