Feedback Control of SPS E-clouds / Transverse Mode Coupled Instabilities[*]

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Abstract

The CERN SPS at high intensities exhibits single bunch transverse instabilities induced by electron clouds and strong head-tail interactions. One proposal to mitigate these instabilities is to use feedback systems with enough bandwidth to sense the transverse position and apply correction fields to multiple sections of the nanosecond-scale bunch. To develop the feedback control prototype, different research areas has been pursed to model and identify the bunch dynamics, design the feedback control and implement the GigaHertz bandwidth hardware. This paper presents those R & D lines and reports the progress until present time.

INTRODUCCION

Intrabunch instabilities induced by electron clouds and strong head-tail interactions are one of the limiting factors to reach the maximum beam currents in SPS and LHC rings [1]. The effect of coating the chambers and adding grooves to the surface of those structures has been studied to mitigate intrabunch and collective effect instabilities induced by electron clouds (e-clouds) [2]. CERN is proposing a plan to coat large part of the SPS and LHC chambers in order to mitigate e-cloud instabilities. Continuous testing of the limitations of these techniques and the design of the necessary infrastructure to apply the coating are currently conducted al CERN [3]. These techniques cannot mitigate transverse mode coupled instabilities (TMCI) and research is conducted at CERN SPS to evaluate the maximum stable beam current that is possible to accelerate adjusting the beam chromaticity.

Feedback techniques can stabilize bunch instabilities induced not only by e-clouds but also induced by strong head-tail interactions (TMCI). Complementary to the plan previously described, 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 [4].

The application of feedback control to stabilize the bunch is challenging because it requires bandwidth sufficient to sense the transverse position and apply correction fields to multiple sections of a nanosecond-scale bunch. These requirements impose technology challenges and limits in the design [5]. 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 PLAN - GOALS

The US and CERN collaboration was proposed recently (in October 2008) to mitigate via feedback e-clouds, TMCI, and other intra-bunch distortions and instabilities at SPS and LHC. The motivation of this collaboration is to control e-clouds and TMCI via GigaHertz bandwidth feedback systems. The immediate goal 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 final system is 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 e-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.
3. Measurements in the SPS machine to validate both the reduced and multi-particle models
4. Development of hardware prototypes to sense and drive the transverse position of different sections of the bunch. Development of hardware prototype of feedback control processing channel.

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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.

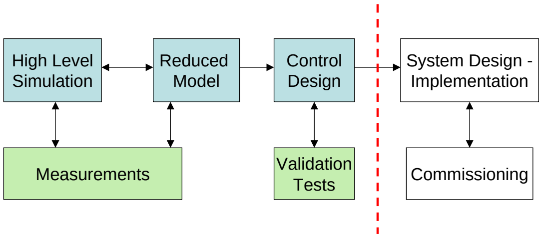

Figure 1: Simplified R & D chart for the development of the wideband feedback control system.

GENERAL OBSERVATIONS FROM MEASUREMENTS AND SIMULATIONS

Several machine measurements where conducted at SPS during summer 2009 and 2010 [5]. The main purpose was to capture the data to analyze different signatures of the bunch dynamics when it interacts with electron clouds. Part of this data has been used to validate multi-particle simulation results, comparing the measurements with simulation results describing similar conditions that the machine. Some representative results form the measurements are shown in the following figures. During the measurements on June 2009, two batches with 72 bunches each were injected to the SPS at 26GeV and 1x10^{11}protons/bunch. The first batch was stable but the second batch exhibited groups of bunches with e-cloud instabilities. Fig. 2 depicts the vertical pick-up signals after equalization to recover the original bunch profile. The SUM signal is the sum of the upper/lower plates of the pick-up and it is proportional to the bunch profile. The DIFF signal is the difference between upper/lower plates and it is proportional to the vertical position of the bunch. The extracted vertical signal shows the vertical position of different sectors of the bunch. It is important to notice that bunch 47 in the first batch is stable but the same bunch in the second batch (bunch 119) shows oscillations. This oscillation is larger in the tail of the bunch (bunch tail : right side of the bunch). It also gives an idea of the bandwidth required for the feedback system. The feedback channel has to sense signals that have a few periods in the bunch span (3 ns.), compute and apply correction signals through the kicker in the same time span.

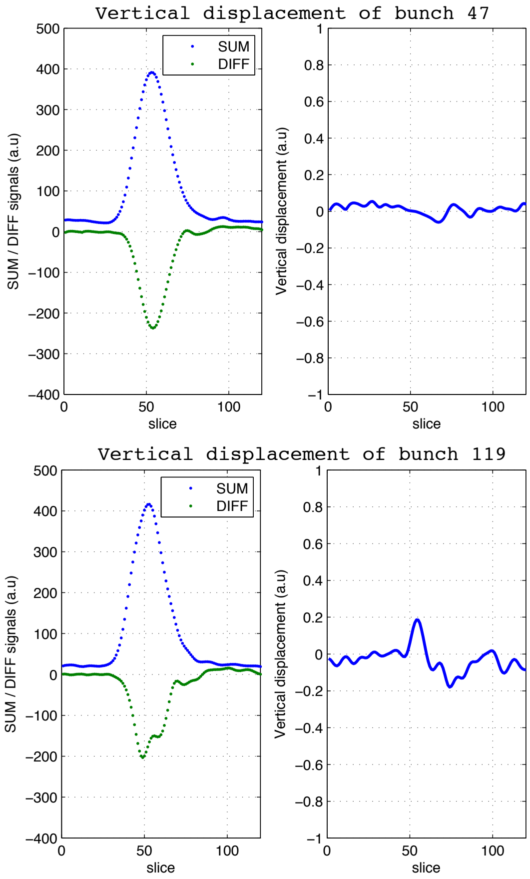

Figure 2: *Upper*: SUM-DIFF signals, vertical displacement for bunch 47. - *Lower*: SUM-DIFF signals, vertical displacement for bunch 119. (*time scale: 2ps/slice*)

Other valuable information from these measurements is that the dynamics for different sectors of the bunch is different. Figure 3 shows the unstable vertical motion for several turns of three representative areas of the bunch. Measuring the frequency spectrum of different sectors in the tail of the bunch, it was observed that the fractional tune shifts due to the e-cloud interaction with the bunch. Fig. 4 depicts the frequency shifting from the nominal tune 0.185 for this machine to 0.197. Simulations have shown larger tune shifts at different energies for sectors in the tail of the bunch.

FEEDBACK STABILIZATION OF INTRA-BUNCH INSTABILITIES

General Considerations for Feedback Design

The proposed digital feedback control topology to stabilize the transverse vertical oscillations within the bunch due to the interaction with the electron clouds and machine impedances is depicted in Fig. 5. The vertical dis-

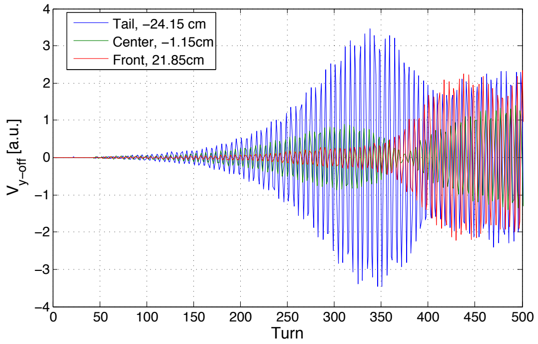

Figure 3: Vertical motion in time domain for different sections of the bunch.

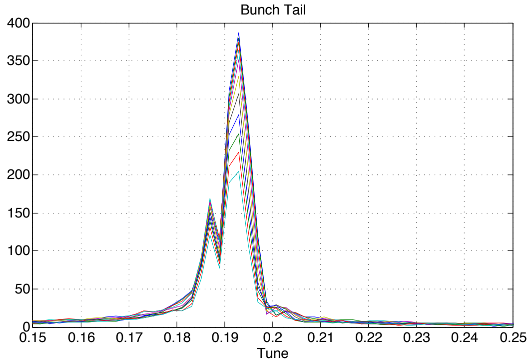

Figure 4: Spectrum corresponding to a few sections of the bunch tail.

placement of different sections along the longitudinal axis of the bunch is estimated and converted to a digital signal V_y by the receiver and ADC. Those samples are processed to generate the control signal V_C and converted to analog signal by the DAC. This signal drives the amplifier and kicker to apply correction fields to multiple sections of the nanosecond-scale bunch.

Based on previous observations, the bunch dynamics interacting with the machine impedance (TMCI) and e-clouds is non linear and unstable. The design of an 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 system has to reject noise and perturbations, like horizontal signals cross-talked with the vertical signals detected.

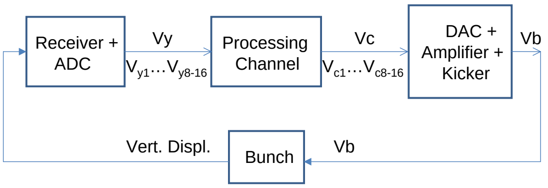

Figure 5: General block diagram of wideband feedback control to stabilize e-clouds/TMCI bunch instabilities.

Hardware prototype

To evaluate the minimum hardware prototype required to control a few bunches in the SPS ring, in addition to the data previously presented, it is possible to analyze the spectrum of the unstable bunches measured during the e-clouds study. Figure 6 depicts the spectrum of the stable bunch 45 (first batch) and the unstable bunch 119 (bunch 47-second batch) for turns 1 - 600. Based on the unstable bunch, it suggests that the bunch spectrum presents frequency components that extent up to near 1 GHz, requiring such a processing capability in the feedback system.

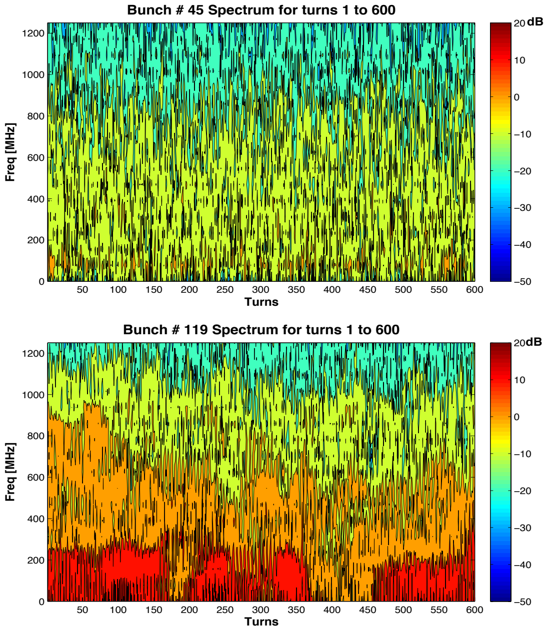

Figure 6: Frequency spectrum for bunch 45 (stable) and bunch 119 (unstable)

The hardware under development consists of a digital processing channel, sampling the signals at 4 Giga Samples/sec. This sampling rate is 8 times higher than actual commercial bunch-by-bunch feedback units. A general block diagram of the proposed hardware is depicted in fig. 7. 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 to the limit the complexity of the digital processing channel. Wideband pick-ups already installed in the SPS accelerator (exponential strip-lines) have been used as horizontal and vertical beam position monitors (BPM) for the measurements [6]. One of the pick-ups is planned to be used 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, limiting the maximum frequency of the signal detected up to 1.7 GHz. Similarly, the pick-up used as kicker has a limited bandwidth of about 200 MHz. It is planned to develop and build new BPMs and kickers with required bandwidth above 1-2 GHz. and install them in the machine during the one year shut-down starting in 2012.

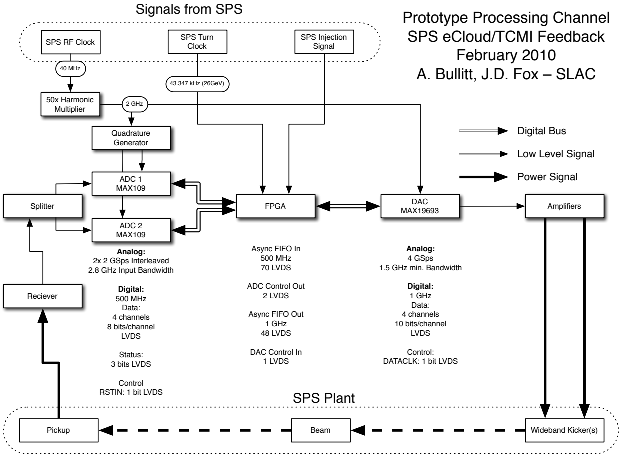

Figure 7: Block diagram of the proposed hardware prototype

Multi-particle Simulation Codes - Feedback Control Models

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 multi-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 [7]. The effort now is to include in those simulation codes realistic models of the feedback system to have a test-bench to analyze the impact in the stability and final emittance of the bunch of finite number of samples per bunch, hardware limitations, bandwidth and noise. Figure 8 depicts a block diagram of the model included in multi-particle simulation codes to represent a realistic feedback channel and analyze the principal limitations in the feedback control introduced by the hardware. The receiver, amplifier and kicker are modeled introducing the real frequency response. Additionally, the amplifier and kicker have limited power capabilities, and noise and spurious signals perturbs the feedback signal detected representing the vertical displacement of different parts of the bunch. In that figure, it is important to observe that the bunch is modeled using multiple particles but the main information linking the bunch dynamics and the feedback system is described by the coordinates of 64 longitudinal slices. The feedback channel uses the information of 8 samples that correspond to a sampling frequency of 4 G Samples/sec (More samples, *e.g. 16 samples*, can be included to represent higher sampling rates in the processing channel). All these constraints affects the stability and performance of the system.

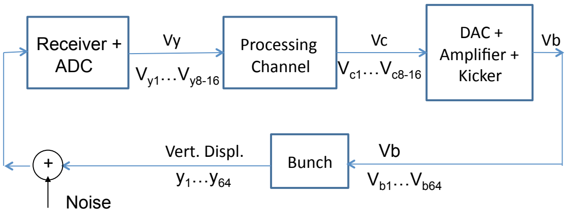

Figure 8: Block diagram of the feedback system modeled in multi-particle code simulators (CMAD-Warp-HeadTail)

Reduced Mathematical Models of Bunch Dynamics - Identification

Development of reduced mathematical models to describe the bunch dynamics is important to design the feedback control taking into account not only the intrinsic bunch dynamic but also noise, system perturbations and other uncertainties and limitations. Simple models consisting of a set of coupled oscillators have been evaluated comparing their behavior with results from simulations based on multi-particle codes and measurements. Presently a set of oscillators with time-variant parameters is under study to model the vertical displacement of different areas of the bunch and take into account the synchrotron motion of the particles within the bunch.

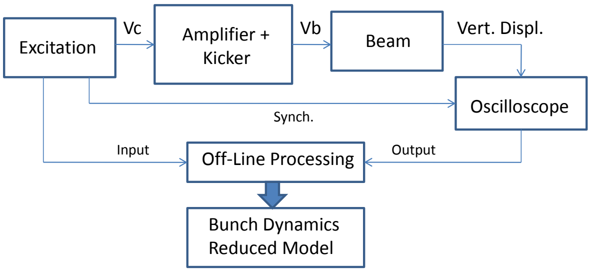

Figure 9: Set-up for reduced model identification of bunch dynamics.

The parameters of the reduced model are identified from measurements. A research effort is in place to generate tools to be able to identify the bunch dynamics directly form measurements in the machine based on the reduced models. An identification technique has been used to define the growth rate and fractional tunes of different sections of the bunch using the measurement of unstable oscillations as those depicted in Figs. 3 and 4. It is planned to identify the bunch dynamics in a more controlled behavior stabilizing the beam and driving the bunch by injecting sequences of random noise. The parameters of the reduced model can be calculated by analyzing the vertical displacement response of the bunch to that stimulus. Figure 9 depicts the block diagram of the system identification set-up. The bunch is driven by a random sequence V_C generated by the excitation and the bunch vertical displacement is estimated by post-processing the oscilloscope measurements. Off line processing using identification routines based on a reduced model of the bunch are used to calculate the model parameters. Based on data generated by using multi-particle simulation codes, an example of the identification test is shown in Fig. 10. This figure depicts the vertical displacement of different longitudinal bunch slices (Samples 9 - 11) when the bunch is driven by a random sequence (Measured Output - Solid Lines). The estimated output depicts the response of the identified reduced model of the bunch to the same random excitation.

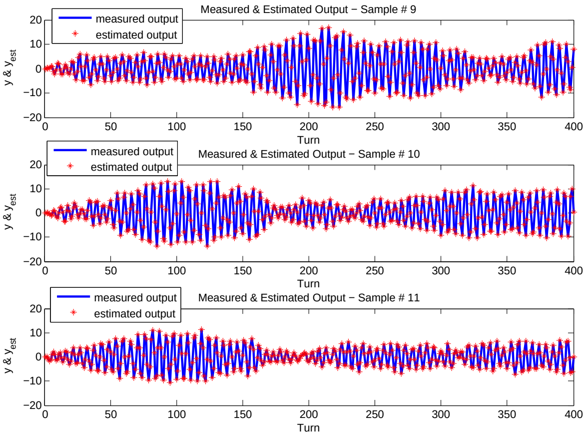

Figure 10: Response of identified reduced model.

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SPS MACHINE MEASUREMENTS

Data collected and results from SPS machine developments and measurements (MD) have been very useful to validate results and adjust parameters in the multi-particle simulation codes. Conducted MDs have measured the natural behavior of the bunch dynamics interacting with electron clouds. To improve the multi-particle simulation codes and incorporate the feedback processing channel, more measurements in the machine are necessary to characterize the dynamics when the bunch is driven by an external excitation. In the next MD (Spring 2011), it is planned to drive the beam with the existent kicker installed in the SPS machine using a set-up similar to the one depicted in Fig. 9. The main goal with these tests is to drive different longitudinal sections of the bunch near the e-cloud instability threshold. These tests will allow measuring vertical tune shifts due to the e-cloud interaction with the bunch and also collect data to test the bunch dynamics identification algorithms. Driving tests are important to validate previous measurements conducted to estimate the kicker gain and strength and the power levels necessary to drive the beam. These results will give solid data necessary for the design of the new wide-band kicker. Additionally, because the excitation board depicted in Fig. 9 has the basic functions of the back-end of the feedback control system prototype, this MD will be very useful to test the timing and synchronization with the SPS machine and quantify timing errors.

Plans for SPS shutdown

The dedicated hardware installed in the SPS to be used by the wideband feedback system has limited frequency response and power capability. The goal during the SPS shutdown is to replace this hardware. New wideband BPM is being designed at CERN and an accelerated research program to study different kicker options is conducted by the collaboration. After choosing the best option for the kicker technology, the idea is to build a prototype and install it in the SPS ring during the shutdown.

CONCLUSIONS

This paper presented the R& D plan and progress directed toward the control of transverse intrabunch instabilities using Giga Hertz bandwidth feedback techniques. To design and build a prototype to control a few bunches in the SPS ring, a collaboration between US Labs and CERN has been established. This collaboration has identified different important areas that includes the modeling and measurement of the bunch dynamics interacting with e-clouds and the machine impedance, the model-based design of the control feedback algorithms and the development of wideband hardware to implement the feedback system. Part of this hardware will be installed during the SPS shutdown to have the appropriated feedback control implementation to control a few bunches and demonstrate the feasibility and quantify the limitations of this feedback technique.

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REFERENCES

[1] G. Arduini *et al.* 31^{st} Advanced ICFA Beam Dynamics Workshop Napa, CA, USA, CERN-2005-001.

[2] F. Caspers, S. Federmann, E. Mahner, P. Pinto, D. Seebacher, M. Taborelli, B. Salvant, C. Yin Vallgren, "Electron Cloud Measurements of Coated and Uncoated Vacuum Chambers in the CERN SPS by Means of the Microwave Transmission Method," 1^{st} International Particle Accelerator Conference: IPAC'10, Kyoto, Japan, May 2010, pp TUPEA076.`http://www.JACoW.org`.

[3] Christina Yin Vallgren, *et al.* "Amorphous Carbon Coatings for Mitigation of Electron Cloud in the CERN SPS," 1^{st} International Particle Accelerator Conference: IPAC'10, Kyoto, Japan, May 2010, pp TUPD048. `http://www.JACoW.org`.

[4] J.D. Fox, T. Mastorides , G. Ndabashimiye, C. Rivetta, D. Van Winkle, J. Byrd, J-L Vay, W. Hofle, G. Rumolo, R. De Maria,"Feedback Techniques and Ecloud Instabilities - Design Estimates," Particle Accelerator Conference PAC 2009, Vancouver, BC, Canada, May 2009. `http://www.JACoW.org`.

[5] J.D. Fox, A. Bullitt, T. Mastorides , G. Ndabashimiye, C. Rivetta, O. Turgut, D. Van Winkle, J. Byrd, M. Furman, J-L Vay, W. Hofle, G. Rumolo, R. De Maria. "SPS Eclouds Instabilities - Analysis of Machine Studies and Implications for Eclouds Feedback," 1^{st} International Particle Accelerator Conference: IPAC 2010, Kyoto, Japan, May 2010, pp. WEPEB052.`http://www.JACoW.org`.

[6] R. Di Maria *et al.*, "Performance of Exponential Coupler in the SPS with LHC Type Beam for Transverse Broad-band Instability Analysis," 2009 DIPAC MOPD17.

[7] Jean-Luc Vay *et al.*, "Update on Electron-Cloud Simulations Using the Package WARP-POSINST," Particle Accelerator Conference PAC 2009, Vancouver, BC, Canada, May 2009, pp. FR5RFP077 `http://www.JACoW.org`.