SPS Intra-bunch Feedback MD Data Analysis
LARP CM20 / HiLumi Meeting

O. Turgut[1,2], J. Cesaratto[1], J. Fox[1,2], C. Rivetta[1], S. Johnston[1,2], W. Hofle[3], G. Kotzian[3], U. Wehrle[3], A. Drago[4]

[1]SLAC National Accelerator Laboratory
[2]Stanford University
[3]CERN
[4]INFN-LNF

April 9, 2013

Outline

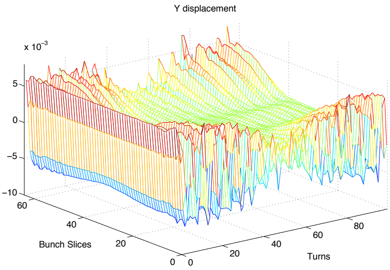
- I am going to review methods and initial analysis results of recent machine experiments carried out using feedback demo system that we developed at SLAC.
- Specifically, I will talk about:
  - Experimental setup
  - Excitation Signals and Open Loop Excitation
  - Analysis of Open Loop Measurements
  - Analysis of Closed Loop Measurements
  - Analysis of Driven and Closed Loop Measurements
  - Future Work

Why do we do beam measurements?

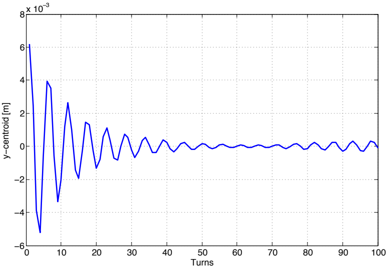
- Simulations and real measurements are two important aspects of intra-bunch feedback.
- We need to take advantage of having two important resources for all kinds of analysis and control techniques that we are developing.
- Similar techniques and methods can be used in both approaches.
- This gives us great opportunity to compare and do benchmarking of each system against each other :
  - Do simulations agree with real beam measurements?
  - We can explain interesting phenomena that we see in the beam by searching over different parameter sets in simulations.
- Simulations will also allow us study all kinds of different control techniques during times that we don't have access to the machine.
- We need to validate simulation results against MD data, and we need to improve simulations in such a way that they account for all physical constraints that we have in reality.

Examples of Simulations

- To define different scenarios and tests during the MDs, the behavior of the system operating in closed loop was studied using macro-particle simulation codes (HeadTail, CMAD) and reduced models.
- Here is an example of feedback system integration to simulation. We can reproduce the measurements we had with our feedback demonstration system.



(a) Signal Processed by Feedback Channel

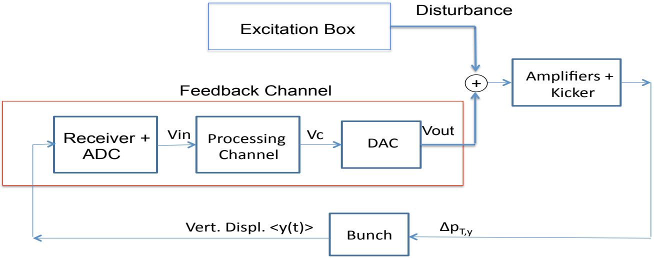


(b) Vertical Off Set Damping of Centroid Motion

Goal of Driven Measurements

- Feedback control design techniques require knowledge of a reduced model that represents the dynamics of the system.
- We need to estimate/extract the parameters of this model that describes the intra bunch dynamics.
- Driving the beam and measuring the vertical motion help us characterize the intra bunch dynamics.
- When bunch is controlled in closed loop similar measurements allow us to identify the impact of feedback system parameters in the bunch dynamics.

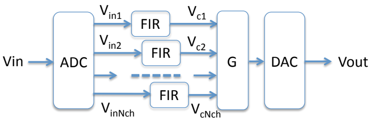
Measurement Setup



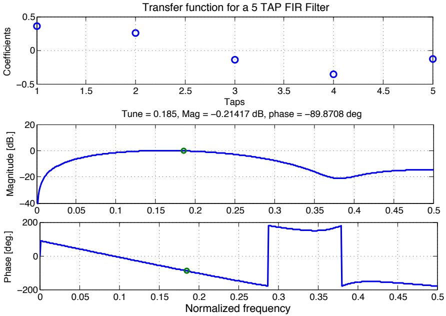
- Open loop measurements
  - We chose to use a band-limited chirp signal to excite motion at betatron frequency f_β, and side bands $f_\beta \pm f_s$,$f_\beta \pm 2f_s$ ...
- Closed loop measurements
  - Feedback changes the dynamics of the system. Impact of feedback on beam dynamics can be studied for different feedback parameters.
  - Stabilize unstable beam!

Feedback System - Processing Filter

- Dipole signal (△) is sampled at 3.2 GS/s (16 Samples).
- This system uses same filter for every slice for slice by slice feedback.



(c) Processing Channel



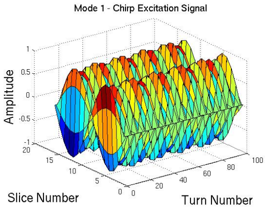
(d) Frequency Response of 5 Tap Filter

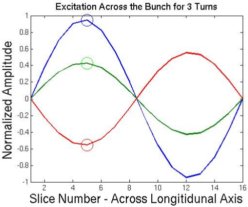
$$V_{Ci}(kTs) = C_1 V_{IN_i}((k-1)Ts) + C_2 V_{IN_i}((k-2)Ts) + \cdots + C_5 V_{IN_i}((k-5)Ts)$$

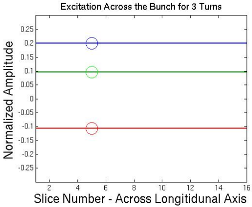
- As it can be seen from the equation, each filter uses the information from a certain slice for some number of turns to generate corrections for the same slice.

Excitation Signals

- On top of existing excitation techniques, the hardware we developed can generate any arbitrary waveform to drive the bunch vertically.
- The spatial characteristic and the frequency characteristic (frequency sweep) along the turns can be set independently.





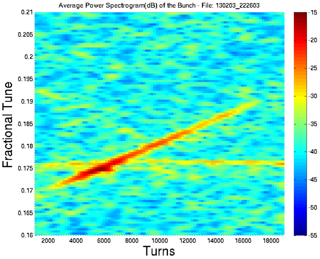


(e) HeadTail Shaped Chirp (f) HeadTail Across the Bunch (g) Mode 0 Across the Bunch

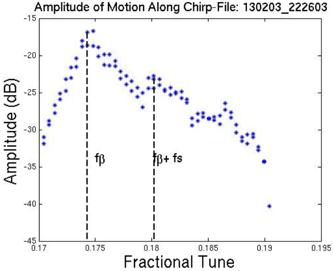
- During recent MDs we excited the beam using both Mode 0 and HeadTail shaped chirp excitations.

Case 1 : Open Loop Mode 0 Chirp Excitation

- Open loop excitations are useful for understanding bunch dynamics, i.e. natural damping.
- Here is an example of mode 0 shape band-limited (0.17 - 0.19) chirp open loop excitation.



(h) Mode 0 Chirp Excitation

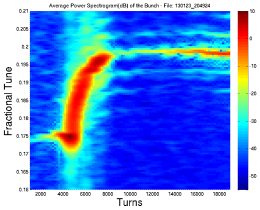


(i) Bunch Response

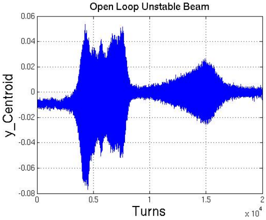
- As it can be seen the shape of excitation across the bunch matters! Using a mode 0 shaped chirp excitation, we excited the bunch more at betatron frequency compared to the motion at the frequency of first and higher side-bands.

Case 2 : Feedback on Unstable Beam

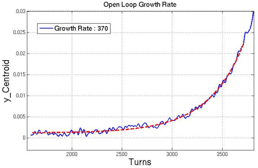
- Bunch becomes unstable at about turn 3k by sweeping the chromaticity negative.
- When there is no feedback, bunch is unstable from betatron tune oscillation and charge is lost.



(j) Unstable beam



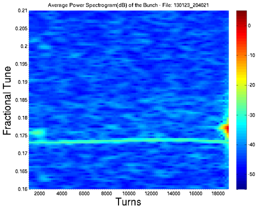
(k) Centroid Motion



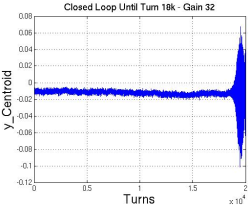
(l) Growth Rate

Feedback Control of Unstable Bunch

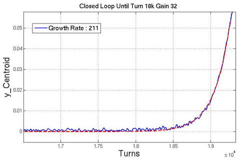
- Feedback stabilizes the bunch up to 18k turns! Feedback gain: 32



(m) FB in ON



(n) Centroid Motion

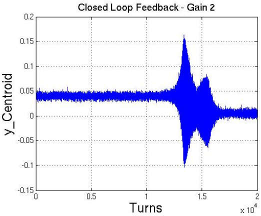


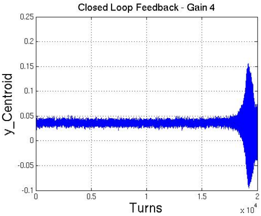
(o) Growth Rate

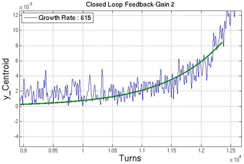
- The chromaticity vs time has a negative slope.
- Feedback applied from turn 3k to 18k.
- After we turn the feedback off at 18k we see an exponential growth rate.

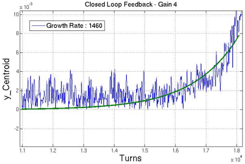
Impact of Feedback Gain on Unstable Beam

- Feedback is on throughout 20k turns.
- Growth rate gets slower as you increase the feedback gain.
- We compare growth rates until DAC signal saturates.
- Apparently, gains of 2 and 4 are not enough to stabilize the beam. Gain 8 stabilizes the system.



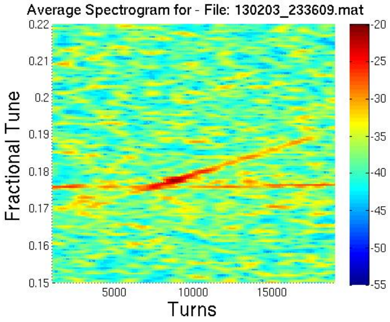




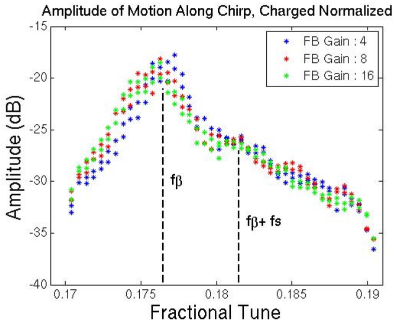


Case 3 : Closed Loop Measurements

- Bunch was driven by a chirp signal to excite the motion at f_β and $f_\beta + f_s$.
- The effect of varied gains on bunch dynamics is studied.
- Following is an example of mode 0 chirp excitation closed loop measurements with gains of 4, 8, 16.



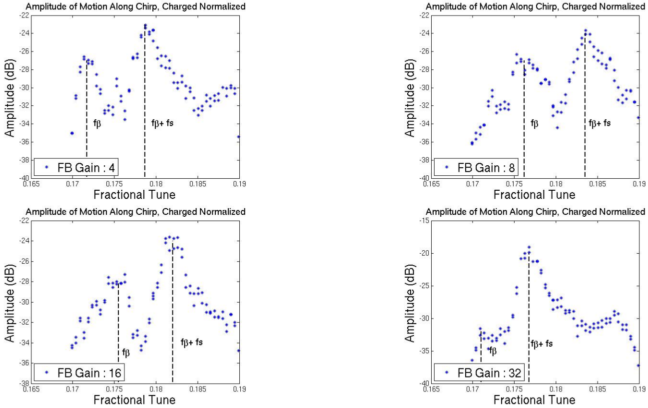
(p) Feedback Gain : 8



(q) Varied Gain

Effect of Different Feedback Gains

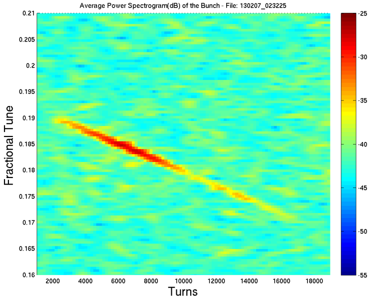
- We excited the bunch with frequency sweep (0.19 - 0.17) and mode 1 shape across the bunch. We closed the loop with different gains.



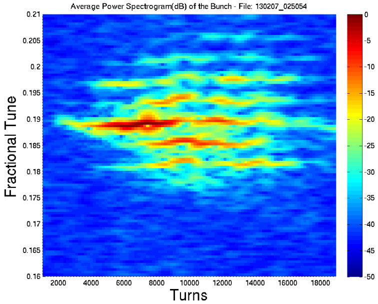
- The motion around betatron tune is more heavily damped with increasing gain.
- As a clear example of how bunch dynamics are changing with feedback, as gain increases the motion around first side-band becomes more unstable.

Case 4 : Closed Loop Grow / Damp

- Closed loop grow/damp tests were conducted. Negative feedback is applied to stable beam until 4k turns. Positive feedback is applied between turns 4k - 12k. Negative feedback is applied again after turn 12k to the end.
- Note the different response of the beam for different positive feedback gains.
- Many modes got excited with higher gain in positive feedback.



(r) FB Gains of -16/+16/-16



(s) FB Gains of -16/+64/-16

Summary - Future Work

- Today I showed a glimpse of what we are heading towards in terms of data analysis.
- Feedback control of intra bunch instabilities requires the coordination of multiple efforts:
  - Hardware development.
  - Reduced order modeling.
  - Simulations and MDs.
- Measurements and data analysis is a critical part of reduced order modeling and system identification.
- During this shut down period we are going to focus heavily on analysis of the huge amount of data we took in 2012 and 2013.
- This effort is in parallel with hardware development efforts, since specifications of hardware are partially dependent on the information we get from measurements.
- The goal is to prepare fully during this shut down period in order to be able to deploy our algorithms and hardware immediately after LS1.