Control of Intrabunch Dynamics at CERN SPS Ring using 3.2 GS/s Digital Feedback Channel

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BROADBAND TRANSVERSE FEEDBACK SYSTEM - DOE LARP / CERN

- Motivation: Control electron-cloud (ECI) and Transverse Mode Coupled (TMCI) instabilities in SPS and LHC via broad-bandwidth feedback system.
    - Anticipated instabilities at operating currents
    - Complementary to electron-cloud coatings, grooves, etc.
    - Complementary to TMCI mitigation techniques
    - Intrabunch Instability: Requires bandwidth sufficient to sense the vertical position and apply correction fields to multiple sections of a nanosecond-scale bunch.
- US LHC Accelerator Research Program (LARP) has supported a collaboration between US labs (SLAC, LBNL) and CERN
    - Large R & D effort coordinated on:
        - Non-linear Macro-particle simulation codes (LBNL - CERN - SLAC)
        - Dynamics models / feedback models (CERN - SLAC)
        - Machine measurements- SPS MD (CERN - SLAC)
        - Hardware technology development (CERN - SLAC)

Machine Development Measurements

Goals

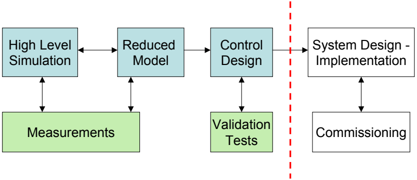
- Be able to design feedback systems and develop diagnostic tools to control intrabunch instabilities
- Fully understand the limitations of feedback techniques to mitigate ECI & TMCI in SPS and other machines.

SPS end of run 2012

- We built the first version of a proof-of-principle prototype for closed loop tests in SPS, using existing kicker and pick-up.
- Commissioned the feedback channel and conducted measurements in closed loop by driving the bunch and observing its response or stabilizing an unstable beam.
- Limited hardware (RF power, kicker bandwidth) defined MD conditions to single bunch, normal intensities, at injection energy, etc.

Validating Models Through Machine Measurements

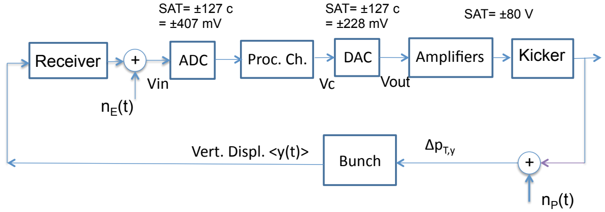
SPS end of run 2012



- Explore the behavior of the feedback channel and collect enough data to validate the macro-particle simulation codes and reduced order models of the bunch
- Validate models, to predict the behavior of improved hardware, e.g., bandwidth, RF power, control filter.
- After the shutdown, new kickers-amplifiers will be installed and the feedback channel will have the capability to operate with multiple bunches at high intensity, follow bunch acceleration, work with SPS Q20 optics, etc.

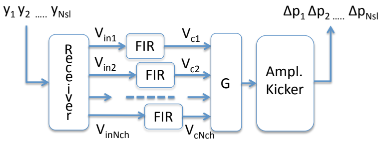
Feedback System

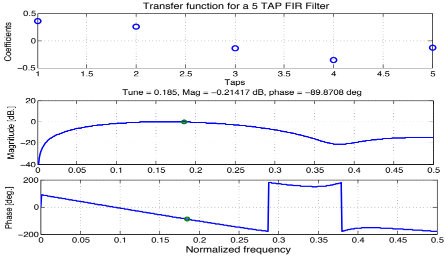
Block Diagram



4 GS/sec. digital channel. Flexible reconfigurable processing - 2 ADCs / 1 DAC
Analog equalization of pick-up and cable transfer functions.

Detail of processing channel and filter



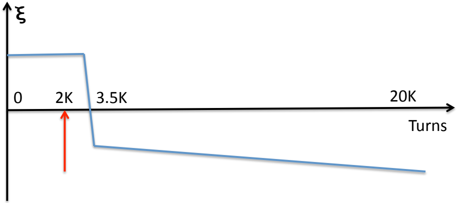


16 samples across 5ns bucket
16 tap FIR filters
Filter paramaters: Gain, Phase

MD results

Control of mode 0 instability with feedback

- To generate an unstable bunch, the chromaticity is changed from positive to negative after injection.
- The beam is unstable in vertical plane: Mode 0 (barycentric motion).
- The feedback loop is closed at turn 2000. Depending upon the gain loop G, it stabilizes the bunch.

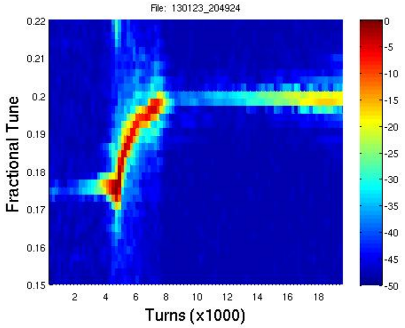


- Around turn 4000, the vertical motion growths with a time constant $\tau \simeq 350$ turns.
- At turn 20K, the growth time constant is $\tau \simeq 200$ turns.

MD results

Control of mode 0 instability with feedback

- Spectrogram of the vertical beam motion. Open Loop, Closed Loop.



Open Loop, bunch unstable around turn 3000

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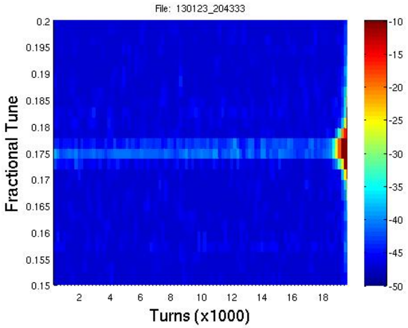
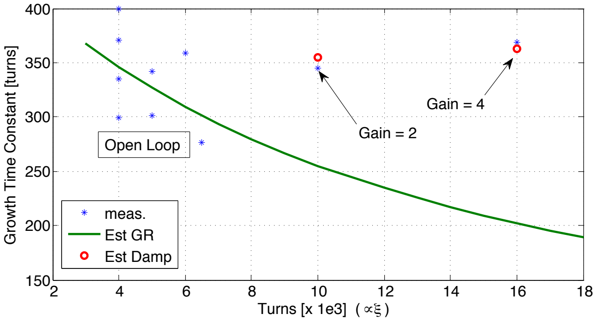


Closed Loop from turns 2K-18K, stabilizes the bunch up to turn 18K

Unstable bunch, impact of feedback gain

- Unstable beam in Open Loop and Closed Loop for gains: $G = 2, 4$
- For gains: $G = 8, 16, \ldots$ the feedback stabilizes the bunch.

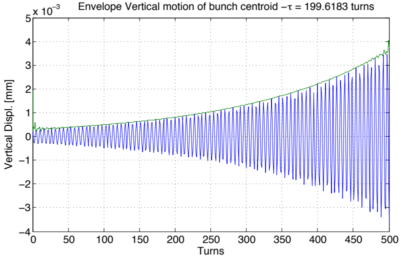


- Assuming a simple damping model for the feedback, $\sigma_D = \sigma_1 G$, the final damping in the system is $\sigma_f(\xi) = \frac{1}{\tau_f(\xi)} = \frac{1}{\tau_{OL}(\xi)} - \sigma_D$.
- From the data: $\sigma_1 = 5.48 \times 10^{-4}$ turns^{-1}.
- For example if $\tau_{OL} = 100$ turns, $G > 17$ stabilizes the bunch.

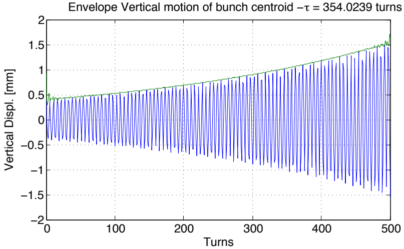
Validation of Reduced Model

Mode 0 (barycentric vertical motion)

- The dipole motion of the bunch in the data analyzed is mainly barycentric (Mode 0).
- The parameters of the model are calculated based on the feedback system in place at SPS ring
- Simulation results show the case for gain $G = 4$.
- $\tau_{OL} = 200$ turns, $\tau_f = 360$ turns, for $G = 4$.



Open Loop



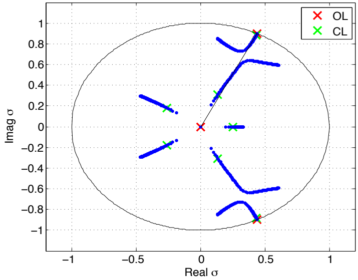
Closed Loop, $G = 4$

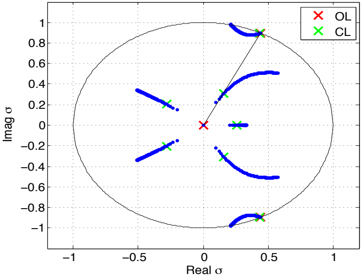
The feedback models in macro-particle simulation codes CMAD - HeadTail were validated using similar approach

Variation of feedback system parameters

Tune measurements

- Controller parameters are Gain, phase. These parameters are changed (G>4)
- The bunch stability is evaluated using root-locus and measurements of the fractional tune.

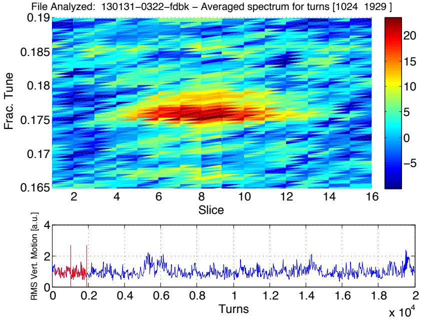




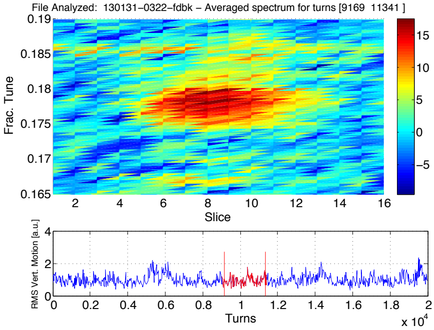
From the controller, the system is sampled at T_{rev}. Plots shows the eigenvalues of the system λ_i in Z-domain ($z_i = e^{\lambda_i T_{rev}}$) for increasing gain G.
Analysis is neglecting the effect of the controllers on the synchrotron side bands of the bunch (Mode 0 dynamics).
Left: Phase of FIR filter set such that the controller phase is $\phi = 70^o$ at $f_\beta = 0.176$
Right: Phase of FIR filter set such that the controller phase is $\phi = 30^o$ at $f_\beta = 0.176$

Variation of feedback system parameters

- Gain = 16, Phase of FIR filter set such that the controller phase is $\phi = 30^o$ at $f_\beta = 0.176$



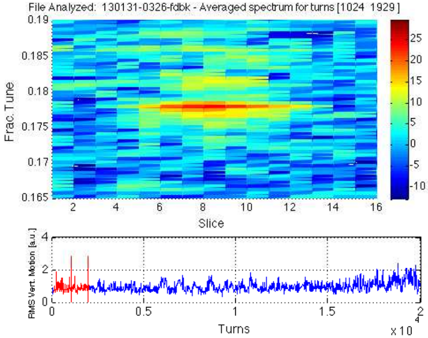
Open loop - Spectrogram for multiple samples across the bunch for turns 0-2000



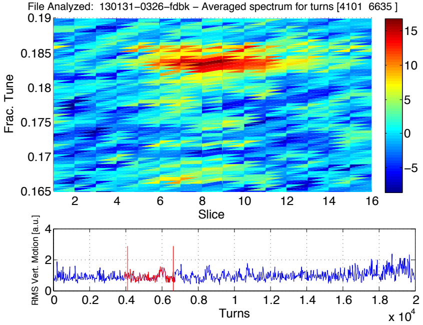
Closed loop - Spectrogram for multiple samples across the bunch for turns 9K-11K

Variation of feedback system parameters

- Gain = 64, Phase of FIR filter set such that the controller phase is $\phi = 30^o$ at $f_\beta = 0.176$

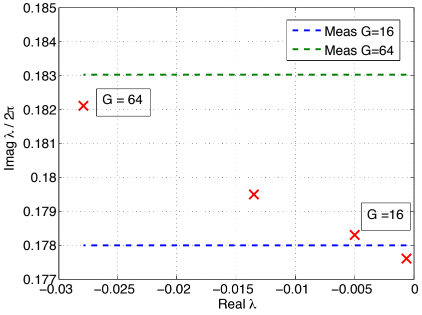


Open loop - Spectrogram for multiple samples across the bunch for turns 0-2000



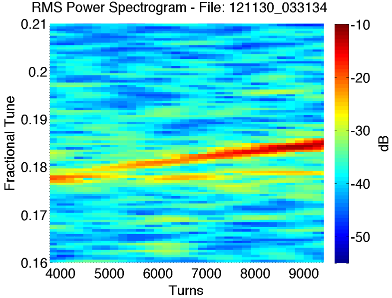
Closed loop - Spectrogram for multiple samples across the bunch for turns 4K-6K

Variation of feedback system parameters



Dominant eigenvalues of the feedback system for G = 8, 16, 32, 64. Comparison with frac. tunes measured for G = 16, 64 phase $\phi = 30°$

Other methods based on driving the bunch to identify the intrabunch dynamics will give better information of the fractional tune and side-band frequencies [Poster TUPAC12 NA-PAC13].



Conclusions

Results from the last MD

- We commissioned the 3.2 GS/s feedback channel (proof-of-principle prototype) at CERN SPS and conducted measurements on single bunch operation.
- We evaluated the performance of the hardware and collect beam data for several feedback configurations to validate simulation models.
- We present some results of the beginning of this validation process.
- Using insight from the measurement and simulations, we define new features to implement into the hardware for future MDs.
- Additionally new technique to monitor and identify the bunch dynamics can be evaluated with real data.

Conclusion

Future Plans

- Design and install 1GHz BW kickers during LS1
- Evaluate and purchase of new amplifiers
- Develop control algorithms and diagnostic firmware
- Be ready to test new feedback prototype system - Start after LS1
- Goal, develop full function system to mitigate ECI - TMCI for the HL-LHC upgrade by 2017.

Thanks to the audience for your attention!!!, ...Questions?

Feedback Systems

General Requirements

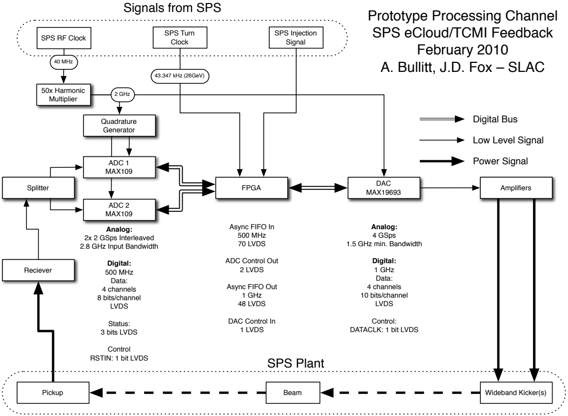
- Original system unstable- Minimum gain for stability
- Delay in control action - Maximum gain limit
- Bunch Dynamics Nonlinear - tunes/growth rates change intrinsically
- Beam Dynamics change with the machine operation
- noise-perturbations rejected or minimized
- Vertical displacement signals has to separated from longitudinal/horizontal signals
- Control up-date time $= T_{revolution}$

Prototype in SPS ring

- Bunch length $\simeq 2.5 - 3.5$ ns
- Sampling frequency $\simeq 4$ G Samples/s

Hardware

Feedback Control Channel - Excitation Prototype



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